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BAROMETRIC PUMPING WITH A TWIST: VOC CONTAINMENT AND REMEDIATION WITHOUT BOREHOLES

FINAL REPORT

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ABSTRACT

Many DOE sites are contaminated with volatile compounds located at relatively shallow depths in the soil. In many cases these contaminants do not pose immediate risk of exposure to the public or site workers, but must nevertheless be remediated. Conventional methods are costly, and removal of contaminants can pose risks to workers. This contract effort developed and demonstrated a passive venting system that removes volatiles from near surface soils capitalizing upon barometric and wind effects. The system, called BERT™ for Barometrically Enhanced Remediation Technique, is unique as a passive venting system in that it does not require boreholes or excavation.

Two processes are utilized to remove contaminants from near surface soils. Changes in barometric pressure induce displacements in soil gas, particularly near the surface. As barometric pressure falls, soil gas is displaced upward. Conversely, as pressure rises, soil gas is displaced downward into the soil. This effect is most pronounced near the soil surface, in high permeability soils with large unsaturated zones. Also, wind passing over a vent pipe projected normal to its velocity has been demonstrated to induce a vacuum that can also be utilized to extract vapors from the soil. A surface cover system has been designed, analyzed, and fielded which capitalizes upon these effects induce upward movement of soil gas. This system incorporates an impermeable surface seal covering the soil, an extraction plenum, and a one-way vent system that allows only removal of soil gas from the system.

The first test installation of the BERT™ system was completed at the Idaho National Engineering and Environmental Laboratory in December of 1996. The system operation has been monitored for over two years. Analysis of the initial data indicates that the system has produced vent flows almost twice that predicted, based on purely barometric pressure-induced flows. Local winds were the cause of the increased flows (averaging 9 m^3/day with peak daily flows of 30 m^3/day). Due to the detail of information provided by the monitoring system, it was also possible to estimate the diffusive flux of contaminants from the surface of the soil if the surface cover was not in place. This was found to be of a comparable magnitude to the measured contaminant removal by the passive venting system. The system design was changed to capitalize on wind effects by increasing the collection plenum area to include the total area covered by the geomembrane (from 707 ft^2 to 10,000 ft^2). This change resulted in almost a four fold increase in average vent flow, to 34 m^3/day. Comparison with estimated and measured contaminant surface flux indicated that the mass removal rate was now higher than the naturally occurring flux from the same surface area had the system not been installed.

This report documents the design evolution, field installation, and monitoring results of the BERT™ field test. Benefits, limitations, and suitable applications are identified for the system.

EXECUTIVE SUMMARY

Many of the planned remediation sites within the DOE complex are contaminated with volatile organic compounds (VOCs). Frequently the contamination sources lie near the surface, and the vapors emanating from these sources disperse over a soil volume much greater than the initial source. The remediation technology developed in this project serves as an in-situ vapor containment and extraction methodology for sites where most or all of the contamination resides in the vadose zone soil. The approach capitalizes on the advective soil gas movement resulting from natural barometric pressure oscillations, supplemented by enhanced vacuums resulting from wind effects on the vent system. Installation and maintenance is inherently inexpensive due to its its non-intrusive nature (no excavation or boreholes required) and passive operation.

This report documents the field demonstration phase (Phase II) of the project. In the initial phase the basic barometric pumping concept was evaluated with respect to its ability to remove or contain volatile contaminants. A model was developed to calculate pressure distributions in the soil given a sinusoidal atmospheric pressure history. This allowed prediction of soil gas displacement, velocity, and the resulting surface flux. A database of contaminants prevalent throughout the DOE complex was compiled, particularly with respect to the diffusive characteristics of volatile contaminants. The soil gas velocities resulting from the installed surface system were compared to equivalent transport velocities resulting from buoyant effects and diffusion downward from the source, with the goal of determining if the barometric pumping installation could prevent diffusion of the source contaminants to the water table. The analysis showed that downward contaminant transport could be mitigated for sources buried 12 to 20 ft. deep.

In the system design* developed during the course of this project, barometric and wind effects are combined to induce a net soil gas removal rate from the contaminated soil. To capitalize on <u>barometric effects</u>, the system design essentially ratchets soil gas out of the near surface by acting as a one-way valve during oscillatory barometric pressure changes. Oscillations in barometric pressure are both diurnal, corresponding to daily heating and cooling of the atmosphere, and of longer time periods, resulting from the passage of weather fronts. In soil exposed to the atmosphere, as the barometric pressure rises, a gradient is imposed on the soil gas that drives fresh surface air into the soil. As it drops, gas vents upward from the soil into the atmosphere. The BERT™ system (for <u>B</u>arometrically <u>E</u>nhanced <u>R</u>emediation <u>T</u>echnology) induces net upward displacement of soil gas using surface features that impede the downward movement of vapors, but allow upward movement. The system incorporates a surface seal, a plenum, and an extraction vent valve. Directly above the contaminant plume a layer of highly permeable material, such as pea gravel, is placed on the surface to form a collection plenum for the upward-moving soil gas. An impermeable membrane is placed over the collection plenum and extends laterally outward over the soil surface to form a buffer zone, which controls the

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*Patented

radial movement of air flowing into the soil during the high-pressure periods. The plenum is connected to the atmosphere with a high-volume one way vent valve, open only when soil gas is moving upward (during a drop in the barometric pressure). In operation the system ratchets the soil gas upward by allowing normal upward flow during barometric lows but restricting downward airflow during high-pressure cycles.

Wind effects result from high velocity air passing over the exposed end of the vent pipe. This induces a vacuum that draws soil gas into the vent system and releases it to the atmosphere. This effect appears to be proportional to the square of the wind velocity. During this project's field demonstration, wind effects dominated the removal rate and led to a design change that boosted system flow by a factor of four.

The Idaho National Engineering Laboratory Radioactive Waste Management Complex (RWMC) is the site for the first demonstration of this barometric pumping remediation system. The Subsurface Disposal Area (SDA) is a 96 acre fenced disposal area inside the RWMC. Mixed wastes containing volatile organic compounds (primarily chlorinated hydrocarbons) and radioactive wastes were buried at the SDA in shallow waste disposal pits, trenches, and soil vault rows. The geology of the SDA consists of surficial sediment deposits overlaying thick basalt deposits. The water table is approximately 600 ft. deep. The BERT™ demonstration system was installed at the INEEL RWMC in December, 1996. The original installation, designed to produce flow based mainly upon barometric processes, consisted of a 100 ft. square surface seal and collection plenum/vent system located at its center. The system is monitored continuously (at 45-minute intervals) for soil gas pressure and temperature, and two or four times daily gas samples are collected for oxygen and carbon dioxide analysis. Detailed soil gas surveys are conducted periodically to quantify the effect of the surface treatment system on the soil gas contaminant concentration distribution.

Evaluation of the initial monitoring data resulted in the following observations:

- The system was extracting soil gas at a rate of twice that anticipated (as predicted by the barometric pumping process alone) likely due to the winds which occur typically at the same time as the drop in barometric pressure. Vent rates averaged 9 cubic meters per day, with peaks as high as 30 cubic meters per day. The predicted average vent flow rate was 4 cubic meters per day.
- Soil gas surveys show the vent system is releasing soil gas with contaminant concentrations diluted approximately 10% (compared to the spatially weighted average of the soil gas 0.5 ft. in the soil beneath the collection plenum) This dilution is suspected due to either slight backflow through the one way vent valve or horizontal leakage beneath the surface seal.
- The surface seal induced the desired controls on the subsurface soil gas pressure gradients. Beneath the center of the installation the gradients were predominantly upward, whereas in the uncovered soil they oscillated uniformly about zero.

The system was then modified to capitalize on the apparent wind effects. In October 1998 the surface seal geomembrane was rolled back and a gravel layer placed over the ground. The geomembrane was then placed over the gravel layer and anchored around the edges. This effectively increased the collection plenum area from the original 30 ft. diameter area to include the entire 100 ft. by 100 ft installation. With the increased collection area (and accompanying reduced resistance to flow) the system total flow rate increased to 34 m^3/day, almost four times the previous value. The increased flow was strongly correlated to winds. The vent system pressure data during the windy periods suggested that multiple vent pipes could be installed on the same system to boost the vent flow proportionally. Comparison to estimated and measured contaminant flux rates from the area of the test showed that the wind-enhanced system was removing more contaminants than would naturally diffuse from the soil had the system not been installed.

The net result is that the BERT™ system removes volatile contaminants at a slow rate while preventing water infiltration into the waste source zone. The benefits of its installation relate primarily to its low cost and risk:

- Installation costs are low because no excavation or drilling is required, and no secondary waste is generated.
- Operating costs are minimal because the system requires no site power and the components are relatively zero-maintenance.
- Risk to workers is very low because no hazardous materials are removed from the site during installation.
- Air emissions are low enough, and dispersed by winds as they exit the vent system, to pose minimal risk to workers.
- Emission rates are sufficiently low to typically be below local or regional thresholds for point source release permitting requirements.

The system is well suited to applications in low risk contaminant settings, where rapid response and remediation are not necessary. Suitable applications include volatile contaminants at relatively shallow depths (less than 20 ft.) in the vadose zone:

- Surface spills of fuels and solvents that would otherwise need to be exhumed for treatment, like thermal desorption.
- Leaking buried pipes or pipe galleries
- Underground storage tank leakage.
- Shallow buried waste
- Residual, shallow volatile contaminants remaining after in-situ treatment or excavation and ex-situ treatment
- Asphalt or cement covers over contaminated sites. A BERT™ installation, using the cover as the impermeable surface seal, will vent accumulated contaminants and water vapor from the soil below the cover.

The BERT™ installation configuration would also be beneficial as a landfill cover. Such an installation would be much simpler (and less expensive) than traditional designs such as RCRA covers, preventing infiltration of water while allowing venting of landfill gases.

1. INTRODUCTION

Many of the planned remediation sites within the DOE complex are contaminated with volatile organic compounds (VOCs). Frequently the contamination sources lie near the surface, and the vapors emanating from these sources typically disperse over a soil volume much greater than the initial source. The remediation technology developed in this project serves as an in-situ vapor containment and extraction methodology for sites where most or all of the contamination resides in the vadose zone soil. The approach capitalizes on wind effects and the advective soil gas movement resulting from natural barometric pressure oscillations. It is inherently inexpensive due to its passive design and low cost of installation.

The original focus of this effort was to design a surface treatment system to capitalize on barometric pressure changes to induce extraction flow. Natural variations in barometric pressure are slight. A typical response in an alluvial setting (Albuquerque, NM) is shown in figure 1. Note that the diurnal change is approximately 5 mbar, and the response at depth is slightly attenuated and delayed (a standard atmosphere is approximately 1000 mbar). These soil gas

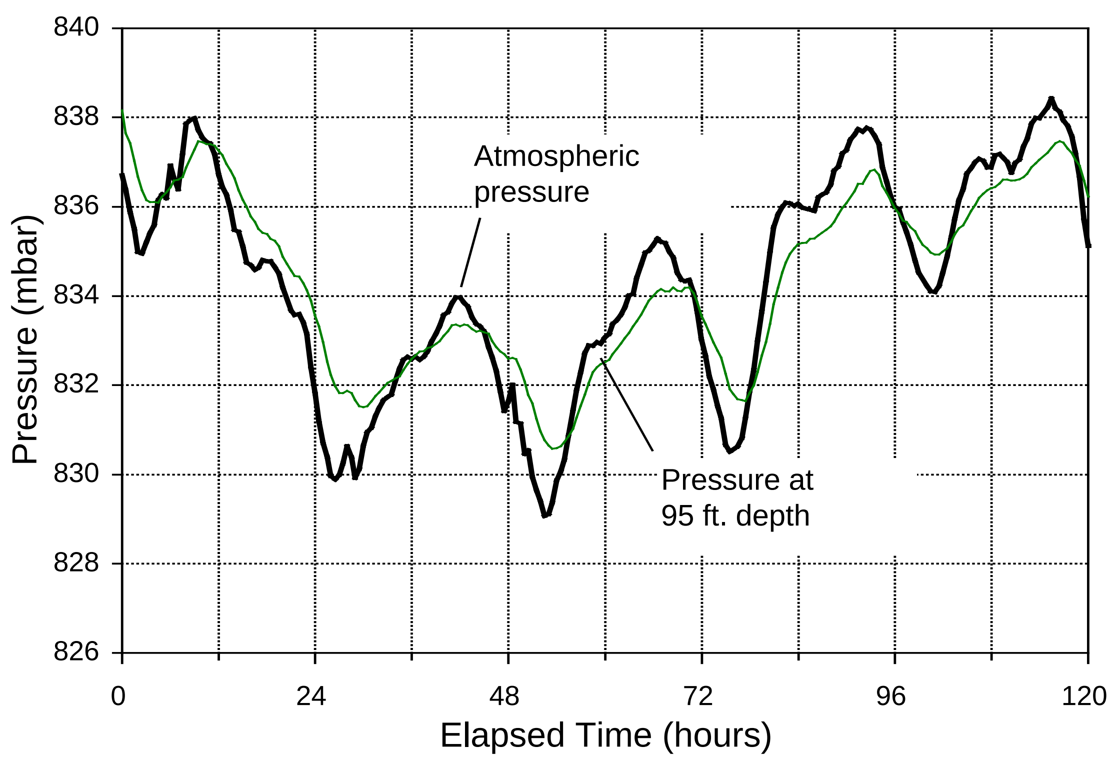


Figure 1. Barometric pressure, and soil gas pressure response at the 95 ft. depth, in alluvium with a water table at approximately 500 ft. (Albuquerque, NM).

pressure gradients induce flow, especially if the soil is short-circuited by an open borehole.

Barometric pumping as a remediation technique came about from observations of airflow out of open boreholes while the atmospheric pressure was dropping, and into the holes while pressure was rising. In these applications, a surface casing or well is typically fitted with a one way valve to allow only exhalation of the soil gas. The technique has been applied at several commercial and government sites (including DOE sites at Hanford, Idaho, Savannah River, and Los Alamos), and is applicable to deep contaminant sources. The technology developed in this effort, on the other hand, uses a surface installation to remove contaminated vapors from the soil, avoiding the need for costly boreholes. It is applicable to relatively shallow contaminant sources, and can cover a large area.

In the first phase of the contract, transport simulations evaluated the capability of the surface seal to control soil gas displacements and prevent downward transport of contaminants to the water table. Contaminant transport characteristics were evaluated, meteorological data was reviewed, and variations in the surface seal design were assessed to optimize the system's performance. The data review, analytical modeling, and numerical simulations confirmed that the surface treatment system imposes net upward soil gas velocities at depths typical of shallow soil contamination. Furthermore, the induced velocities were of magnitudes capable of overcoming the downward transport rates due to diffusion and density gradients. The following summaries clarify and support these conclusions.

- Soil gas moves naturally in soil, and its movement is sinusoidal in nature. Its dominant frequency and magnitude are due to the daily 5 mbar variation which results from heating and cooling of the atmosphere. In higher permeability soil, the velocities will be greater for a given atmospheric pressure variation. Peak velocity also increases as the depth to an impermeable layer increases. The peak soil gas velocity, determined by analytically modeling the soil gas response, will range from 0.2 to 0.8 m/day for a typical range in permeability (1 to 10 Darcies) and depths to an impermeable layer of 50 m or more. Under natural conditions, this oscillatory movement results in no net flow because it always returns to its mean value.
- The BERT™ surface treatment (seal, collection plenum, and vent valve) effectively rectifies the sinusoidal soil gas velocity by minimizing the downward component. This results in a net upward component over time, which is at a maximum just beneath the plenum. The maximum attainable (average) soil gas flux at the surface ranges from 0.03 to 0.07 m^3/m^2-day.

The flow rates predicted numerically were compared with processes which would transport contaminants downward toward the water table. These processes are: concentration-induced density gradients, diffusion, and temperature-induced density gradients. Each of these mechanisms results in a maximum transport rate at the source, then a diminishing transport rate as depth increases. The key results of the comparison are:

- The density gradients resulting from the contaminant concentration distribution (due to diffusion from the source) impose a downward flow from the source. The advective velocity resulting from the surface treatment system is capable of exceeding the downward transport rate with a source as deep as 4 m.

- The surface treatment system induces soil gas velocities which overpower the downward diffusion rates. For a planar contaminant source, the net advective upward velocity exceeded downward diffusion of TCE for a source as deep as 10 m.
- Seasonal heating and cooling of the soil surface will cause temperature gradients in the soil which induce density gradients in the soil gas. This is shown to be the easiest of the three transport processes to overcome: the surface treatment causes a net upward velocity almost ten times that required to overcome the temperature induced buoyant flow.

The second phase of the project demonstrated the BERT™ installation at the Idaho National Engineering and Environmental Laboratory. A site was located at the Radioactive Waste Management Complex where chlorinated hydrocarbons had been buried in shallow trenches. The system was installed in December of 1996. Monitoring continued through 1997 and early 1998. The data indicated that the system was producing extraction flow more than twice of that predicted, and that this could be attributed to wind effects. It was apparent that wind effects dominated the extraction process, and the installation design was modified to capitalize on those effects. In October 1998 the system design was changed and subsequent monitoring data showed that vent flows are now four times those of the initial design.

The following report sections describe the BERT™ system design, the INEEL installation, operational data from the initial configuration testing period, modifications to the original design to capitalize on wind effects, the resulting performance improvements, and application issues associated with the system.

2. TECHNOLOGY DESCRIPTION

The objective of this effort is to demonstrate a passive venting system capable of removing near-surface volatile contamination without the need of boreholes or site power. The BERT™ system utilizes a unique design incorporating a large-area surface seal, a collection plenum, and a one-way valve that vents the extracted soil gas to the atmosphere at a low rate. The system operation relies upon wind effects and naturally occurring oscillations in barometric pressure.

Changes in barometric pressure induce soil gas displacements in the unsaturated zone. The total amplitude of barometric pressure oscillations ranges from 0.5% (in the case of diurnal variations) to over 2.5% (due to weather front passage) of the atmospheric pressure. Much like the movement of a piston in a cylinder, soil gas near the surface of the soil will displace downward when barometric pressure increases, and upward as barometric pressure falls (figure 2). Under steady-state conditions the displacement is proportional to the magnitude of the pressure change and the depth to a vapor-impermeable boundary, such as the water table. With depths to an impermeable layer of several hundred meters, expected displacements would be on the order of tens of centimeters to several meters. Greater displacements occur in higher permeability soils.

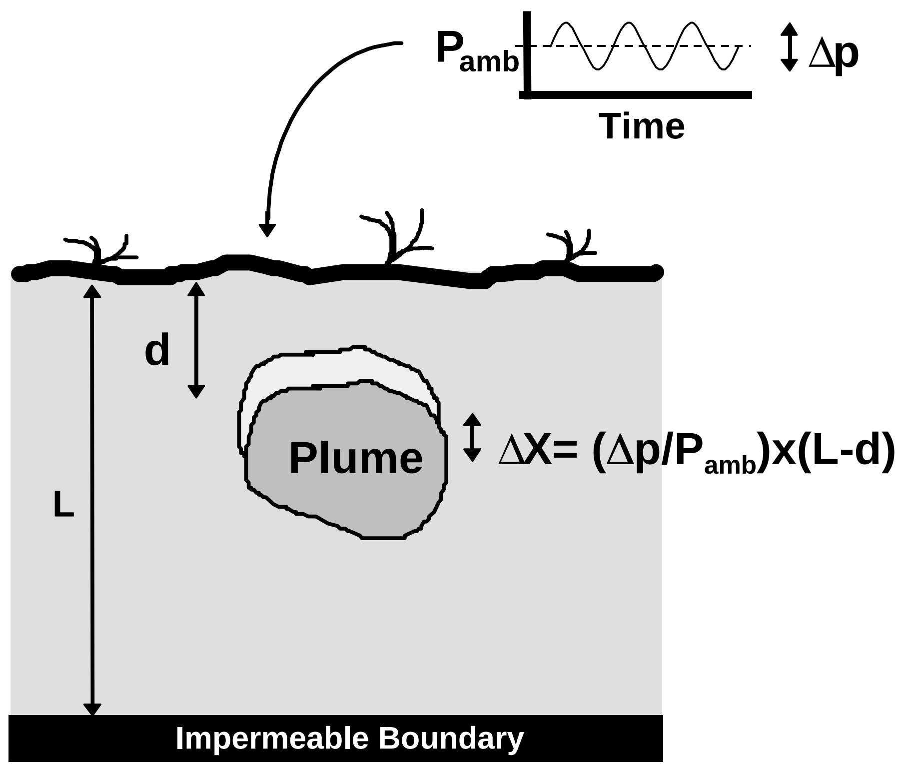


Figure 2. Variations in barometric pressure induce vertical displacements in soil gas.

Another significant process that enhances vapor removal is the relative vacuum generated on a pipe projecting into a moving air stream (normal to the wind direction). Influenced by the Bernoulli effect, this process induces a vacuum of a magnitude proportional to the square of the velocity. At many locations, particularly arid western sites such as Idaho, New Mexico, and eastern Washington, significant winds prevail that can act as steady pumping mechanisms. If applied correctly, this process can overshadow the barometric pressure process and induce much greater soil gas extraction rates.

The BERT™ system (for Barometrically Enhanced Remediation Technology) induces net upward displacement of soil gas using surface features and a vent system that capitalize upon barometic and wind effects.

2.1 Process Description

2.1.1 Barometric Effects

Oscillations in barometric pressure are both diurnal, corresponding to daily heating and cooling of the atmosphere, and of longer time periods, resulting from the passage of weather fronts. Daily variations will average about 4 to 5 millibars (one millibar is approximately one thousandth of an atmosphere) while those due to weather front passage can be 25 or more millibars. As the barometric pressure rises, a gradient is imposed on the soil gas, which drives fresh surface air into the soil. As it drops, gas vents upward from the soil into the atmosphere. The total movement of soil gas is dependent primarily on the magnitude and period of the pressure oscillations, the soil gas permeability, and the depth to an impermeable boundary. This boundary can be the water table, bedrock, or extensive layers of very low permeability material, such as caliche or clay. Since the fractional change in atmospheric pressure is small (typically 0.5 percent) the overall soil gas displacement during the daily cycle is also small (with an estimated range of centimeters to meters).

Displacement of soil gas due to barometric pressure variations can be controlled using surface features that impede the downward movement of vapors, but allow upward movement. The design developed in this project incorporates a surface seal, a plenum, and an extraction vent valve. These components are depicted in figure 3. Directly above the contaminant plume is a layer of highly permeable material, such as pea gravel, which forms a collection plenum for the upward-moving soil gas. A surface seal is placed outward from the collection plenum directly on the soil surface to form a buffer zone that controls the radial movement of air flowing into the soil during the high-pressure periods. The surface seal is an impermeable, rugged material (such as a geotechnical membrane), which forms a no-flow boundary at the ground surface. The plenum is connected to atmospheric pressure with a high-volume vent valve, open only when soil gas is moving upward (during a drop in the barometric pressure). In operation, the system ratchets the soil gas upward by allowing normal upward flow during barometric lows but restricting downward airflow during high-pressure cycles. High-pressure periods result in restricted downward gas movement because the vent valve is closed and soil gas flows around the plume (“inhaling”). When the atmospheric pressure is lower than the soil gas pressure at depth, soil gas flows upward and the surface seal forces the contaminated gas into the plenum, where the opened vent valve exhausts it to the atmosphere (“exhaling”).

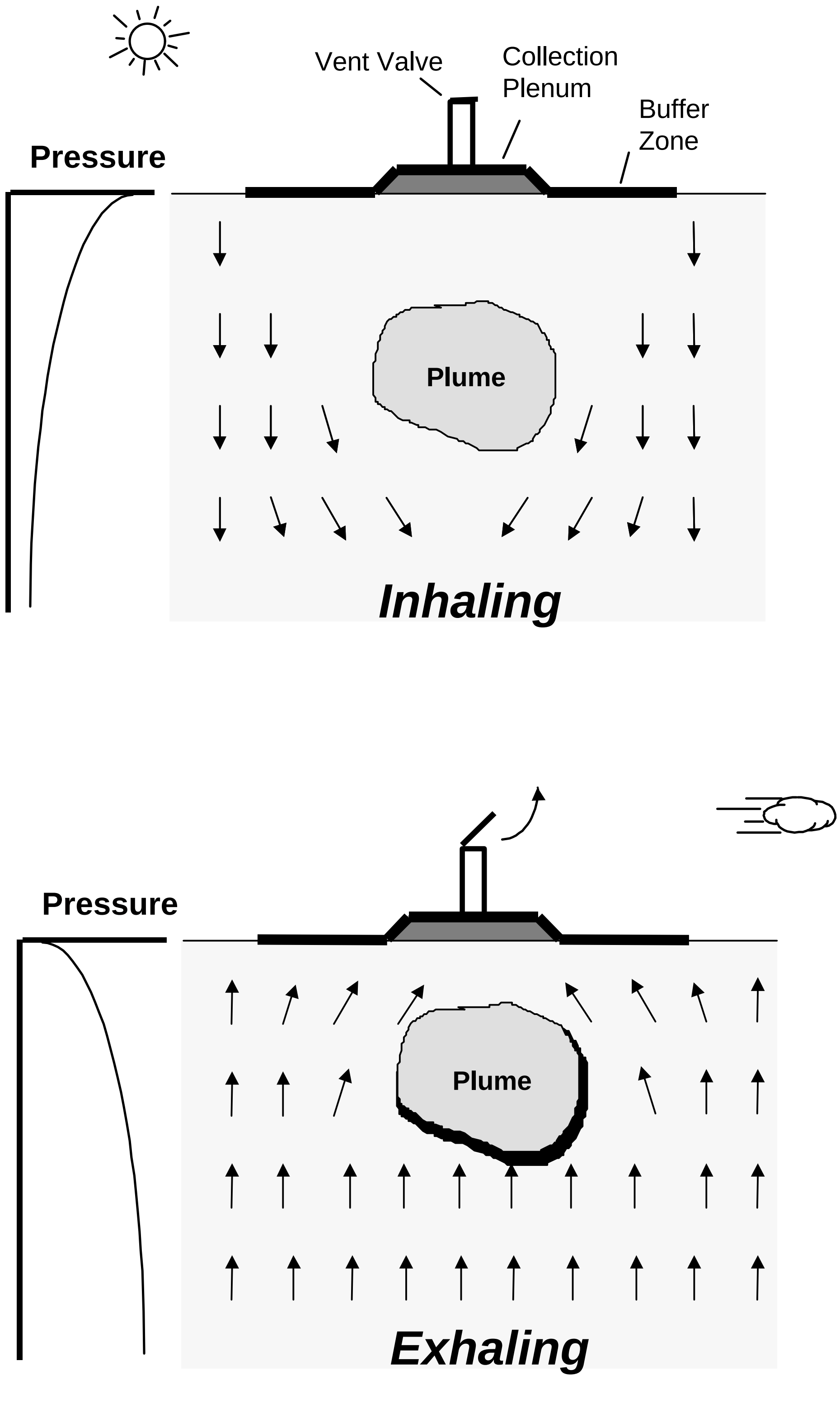


Figure 3. The surface treatment system controls the movement of soil gas due to barometric pressure changes.

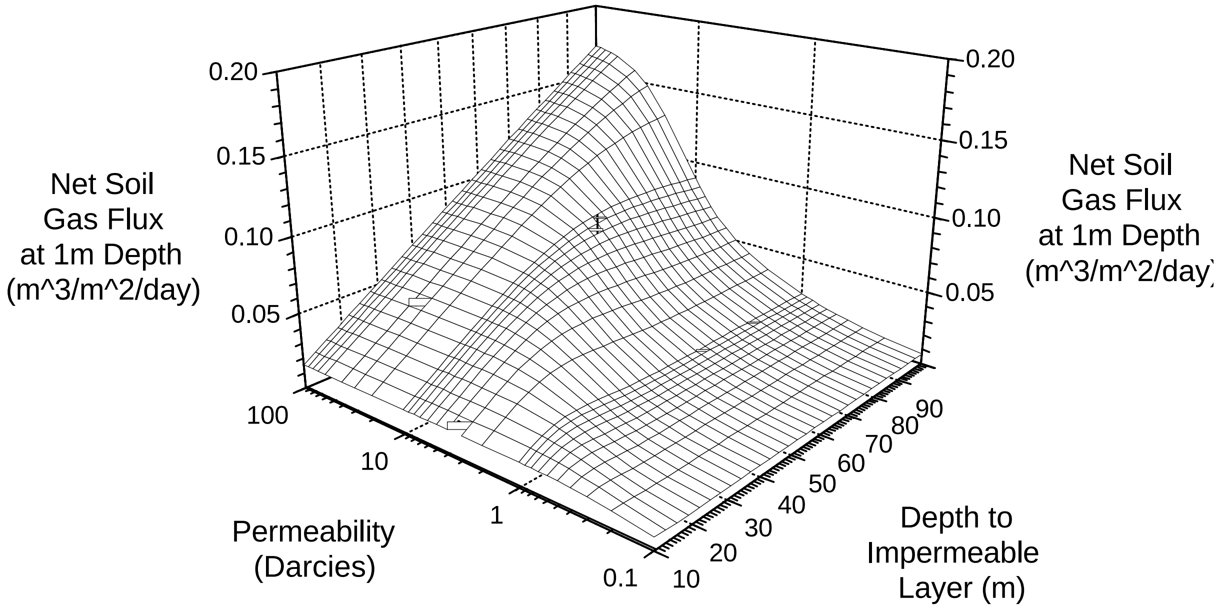


Figure 4. Maximum net upward soil gas flux attainable by the surface treatment system, given daily barometric pressure oscillations of 5 mbar and a soil porosity of 0.35.

The role of the barometric system design is to minimize the downward component the sinusoidal soil gas velocity in the contaminated zone to produce a net upward velocity. The soil gas velocities attainable due to the naturally occurring variations in barometric pressure were determined analytically as a function of the soil permeability and distance to an impermeable layer, such as the water table (Lowry et al. 1996). The average surface gas flux can be determined from the velocity by averaging the upward portion of the oscillatory velocity over a daily cycle and ingnoring the downward component (downward flow is prevented by the surface installation). Soil gas velocity is converted to flux by multiplying by the soil's connected, gas-filled porosity, and is presented in figure 4. The maximum net soil gas flux attainable with the surface treatment system ranges from 0.03 to 0.07 m^3/m^2/day for 1 to 10 Darcy soil, with depths to the impermeable layer exceeding 30 m. For a 10 m diameter plenum, this yields a total soil gas extraction flowrate of 2.3 to 5.5 m^3/day. Given an air filled porosity of 0.35, 6.6 to 15.7 m^3 of soil is flushed per day.

2.1.2 Wind effects

The soil gas pressure gradients resulting from the barometric process are limited in magnitude to the maximum changes in barometric pressure experienced over time. Wind, on the other hand, can impose larger gradients in the soil if the system is designed to capitalize on the effect. The open end of a pipe projecting into a moving air stream will experience a vacuum proportional to the square of the wind velocity. Called the Bernoulli effect, the resulting vacuum is significant as to the pressure gradients it can impose in the soil. In laboratory experiments, where a 4 inch diameter pipe was exposed to wind speed of 12 mph, a peak vacuum was measured of approximately 0.15 inches of water column (37 Pa, or .37 mbar). The vacuum increased proportional to the square of the velocity, and at 30 mph achieved a vacuum of 0.5 inches of water column. This can impose greater soil gas pressure gradients than the barometric pressure variations. Mean wind velocities at or near DOE sites in Idaho, New Mexico, and eastern Washington ranged from 8.3 to 10 mph (Lowry et. al, 1996).

2.2 System Components

In its installed form, the barometric remediation system is depicted in figure 5. The key components are the surface seal, the plenum, and the vent assembly. Both the initial configuration and the wind-enhanced configuration are shown. The basic difference between the two is that collection plenum of the wind-enhanced design lies beneath the entire geomembrane cover area to maximize the extraction rate.

2.2.1 Surface Seal: The role of the surface seal material is to contain soil vapors in the plenum region and prevent flow into or out of the soil in the buffer zone. A further role is to induce a vacuum "boost" when the barometric pressure trend shifts from rising to falling, due to the delayed response of the soil beneath the plenum. Seal material must be resistant to soil moisture, organic contaminants, and sunlight (if exposed), and capable of multiyear emplacements. Suitable membrane materials have been developed for roofing and landfill Installations to fill requirements more stringent than these, so a wide selection of candidate materials is available. EPDM (synthetic rubber) is very rugged and resistant to exposure and was

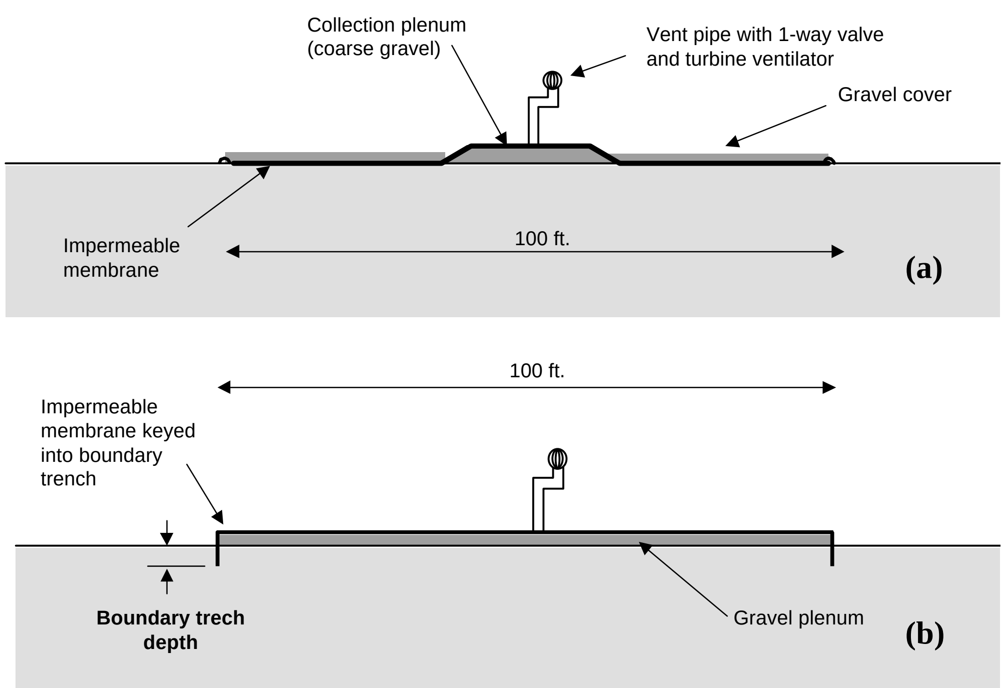


Figure 5. Barometric installation design (a) and wind-enhanced design (b)

selected for this application. The surface seal is one continuous sheet covering both the buffer zone and the plenum area. It must be pliable enough to conform to the contours of the soil (the soil will be leveled to some degree before the seal is applied) and over the plenum. To minimize damage to the geomembrane from abrasion (due to foot traffic), exposure to the elements, or plant/animal intrusion, a shallow layer of pea gravel is placed over the membrane. This serves a secondary role of assuring the membrane is pressed firmly onto the soil to promote a good seal.

2.2.2 Plenum: The plenum serves as a collection manifold for the upward-flowing soil gas during the exhaling cycle of the system. Its basic requirements is that the plenum material have a permeability several orders of magnitude greater than the soil below. It must also be inexpensive, stable, and not pose a puncture threat to the membrane material (no sharp edges). Standard pea gravel fills these requirements with permeability in the range of 1000 to 5000 darcies ($9.87e^{-10}$ to $4.53e^{-9}$ m^2). Since it has such a high permeability, a layer six to twelve inches thick is adequate. In the initial barometric design, the collection plenum covers a fraction of the total cover area (such as 1/3 in the case of the INEEL installation). The wind-enhanced design extends the cover plenum to the outer perimeter of the cover, and anchors the edges of the cover in the soil.

2.2.3 Vent Assembly: The main role of the vent assembly is to allow only outward (exhaling) flow from the plenum volume. Its secondary role is to release the soil vapor high enough into the air to rapidly disperse the contaminants. The assembly consists of a vent pipe

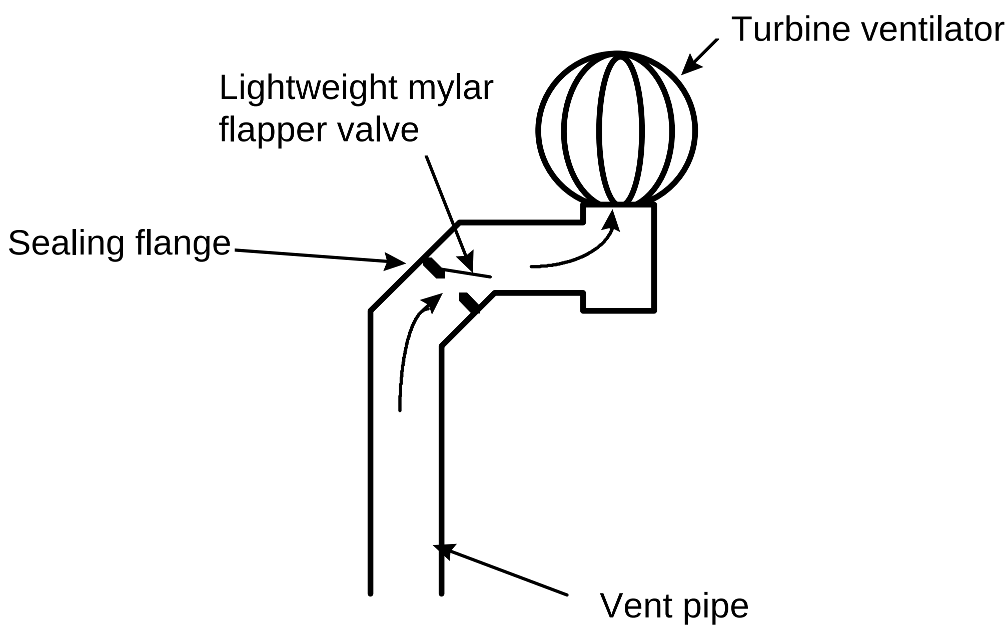


Figure 6. Vent pipe and relief valve configuration, shown with a turbine ventilator as installed in the original barometric pumping design. For the modified installation, the turbine was removed.

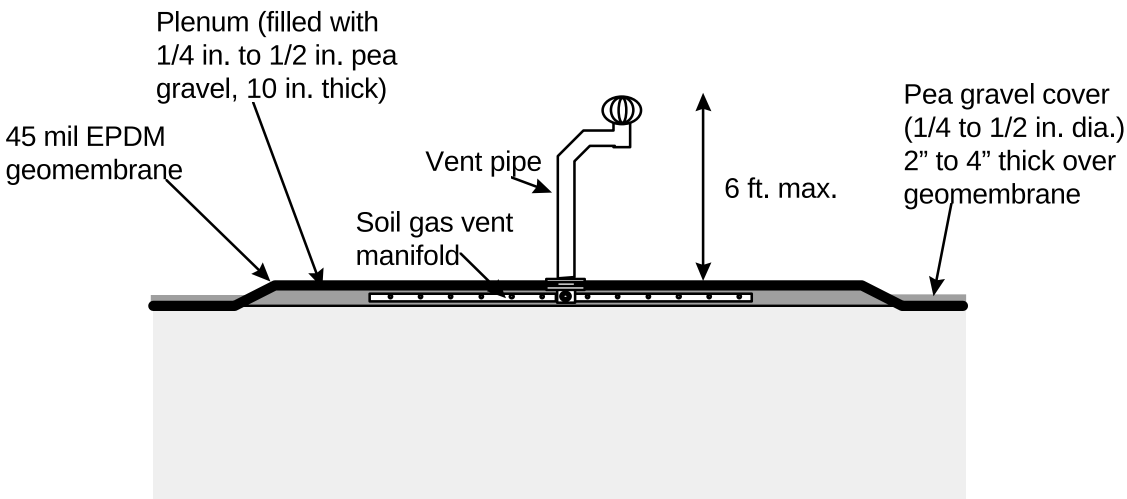


Figure 7. Vent pipe and plenum configuration.

and a one-way valve (figure 6). The surface seal membrane is clamped securely around the base of the vent pipe, which is free standing (figure 7). The vent valve is designed to open at minimal differential pressure while maintaining a seal when no positive pressure differential exists, allowing for flow in one direction only. The approach to the design is to mount a lightweight mylar valve inside the stack vent that will provide a seal by resting its mass on a sealing surface (figure 6). The valve is oriented at an angle off of vertical, designed to open at very low differential pressure (less than 0.1 mbar) yet still be strong enough to prevent backflow. In the original installation a turbine ventilator was mounted on the top of the vent pipe. Laboratory testing conducted by SEA showed, however, that the turbine ventilator actually reduced the maximum vacuum that could be generated, compared to a simple pipe projecting normal into the wind. Consequently the ventilator was removed for the subsequent testing.

2.3 System Cost

Cost of a BERT™ installation is low, primarily due to the lack of earth removal and/or boreholes. The major components of an installation are listed in table 1, which estimates the cost for installation and abandonment of the barometric extraction system. Characterization and monitoring costs are not included here because they are common to any remediation system application. Details of this cost assessment and comparison to conventional remediation approaches are described in (Lowry et al., 1996). These cost estimates were confirmed during the installation of the system at the INEEL. The basic system installation was completed in a week.

The unit cost for this installation is about $\$3.47/ft^2$.

Table 1. Cost estimate of BERT™ installation.

Cost Component	Unit Cost	100 x 100 ft. Installation
Materials:		
Sealant: 45 mil EPDM sheeting	$0.55/ft²	$5.5
Plenum fill and seal cover gravel	$15/yd³	9.2
Vent pipe, flapper valve, turbine ventilator, supports, vapor points	$1K/assy	1.0
Labor:		
Mobilization/demobilization	$1K	1.0
Surface grading and leveling	$45/hr	.72 (16 hr)
Installation (cover, plenum, vent)	$50/hr	3.2 (64 hr)
Abandonment (removal/reclamation)	$50/hr	3.2 (64 hr)
SUBTOTAL		23.8
Escalation (10%)		1.9
SUBTOTAL		25.7
Contingency and Proj. Mgmt. (@35%)		9.0
Total		**$34.7 K**

3. DESCRIPTION OF THE INEEL RWMC INSTALLATION

3.1 Site Description

The Idaho National Engineering and Environmental Laboratory Radioactive Waste Management Complex (RWMC) was selected as the candidate site for demonstration of the barometric pumping remediation system. The Subsurface Disposal Area (SDA) is a fenced disposal area inside the RWMC (figure 8). Mixed wastes containing volatile organic compounds and radioactive wastes were buried at the SDA. Included in the SDA are numerous waste disposal pits, trenches, and soil vault rows. The pits are backfilled excavations with a variety of dimensions.

The geology of the SDA consists of surficial sediment deposits overlaying thick basalt deposits. Irregularities in the soil thickness (ranging from 1 to 23 ft.) reflect the surface undulations of the underlying basalts. The surface soils are typically less than 20 ft. thick and consist of gravely sand and fine-grained eolian deposits. The water table is at approximately 600 ft. The volatile contaminant vapor plume is believed to extend vertically from the ground surface

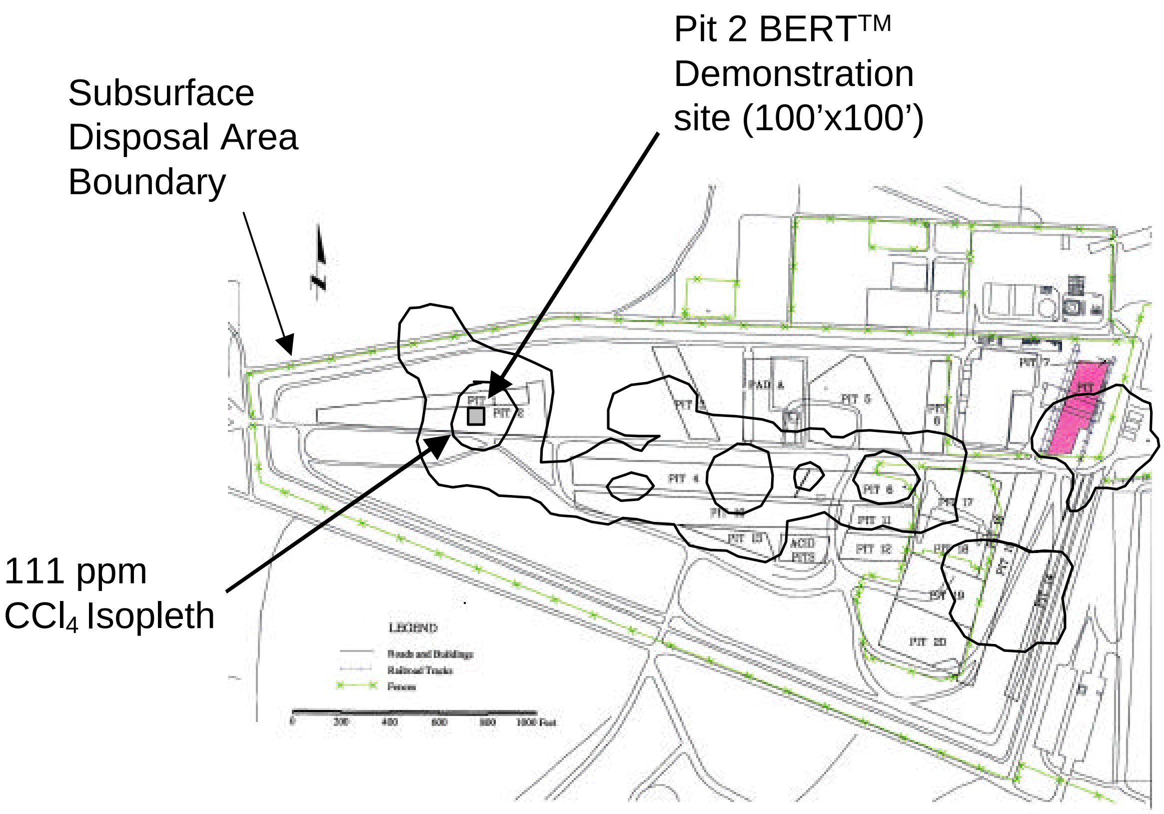


Figure 8. Barometric pumping installation at the INEEL Radioactive Waste Management Complex (RWMC). The surface installation was located over Pit 2 in the northwest sector of the Subsurface Disposal Area. Isopleths are shown for carbon tetrachloride soil gas analysis of samples taken at 30 inch depth.

to the surface of the groundwater at the depth of the aquifer. The bulk of the contamination detected during soil gas surveys is in the form of chlorinated hydrocarbons, dominated by carbon tetrachloride with trichloroethylene, chloroform, and tetrachloroethylene in lower concentrations. Over the entire area of the SDA the peak concentration of any one component during the shallow soil gas surveys was about 1,000 ppm (detected in a 1987 survey near Pit 9). A recent shallow survey (1992) is depicted in figure 8, which shows the isopleths for carbon tetrachloride. The area chosen for this demonstration is identified as Pit 2. In the area of interest the peak contaminant concentration was 111 ppm of carbon tetrachloride. This disposal pit received barrels of sludge between 1954 and 1965.

Active vapor extraction is underway at the SDA using three extraction units. These extraction units are concentrating on volatile contaminants accumulated in an interbed at approximately 100 ft., a relatively thin layer of silty material between basalt units. Chlorinated hydrocarbon contaminant concentrations as high as 6,000 ppm have been detected in these zones, indicative of an accumulation of liquid contaminant. Unit C, the closest to the proposed demonstration site (approximately 250 ft. distant), extracts from a 10-ft. screened well interval centered on the 93-ft. depth.

This area was selected for the demonstration because records indicate significant amounts of volatile contaminants were deposited in a well-defined area, soil gas surveys detected the presence of near-surface contaminant deposits, and the site has a deep water table to maximize barometrically induced soil gas displacements.

3.2 BERT™ Installation

The installation of the remediation system required no excavation, although shallow penetrations in the soil were completed for soil vapor sampling. The site was cleared of vegetation, rocks, and debris prior to installation of the surface components. The vapor monitoring system required installation of soil vapor sampling points to a maximum depth of eight feet.

The initial barometric pumping installation was placed over the contaminated region of interest (see the plan view in figure 9). In the center of the membrane is a collection plenum formed with a coarse pea gravel layer (6” to 12” thick) beneath the geomembrane. Located in the center of the plenum is a vent pipe, which allows soil gas collected in the plenum to vent to the atmosphere (figure 10). The EPDM membrane is 100 ft. square. The area of the surface seal radially outward from the plenum is covered with a layer of pea gravel to provide a positive seal to the soil and prevent movement of the membrane due to high winds. Around the perimeter of the surface seal the membrane is anchored to plastic pipe. This serves as a positive anchor for the membrane perimeter and also prevents water runoff from the surface seal during heavy rains. The completed initial configuration is depicted in figure 11.

After the system operation was monitored for approximately 18 months, design changes were proposed to enhance the extraction flow rate. The geomembrane was rolled back, a gravel layer was placed over the entire covered area, and the geomembrane placed over the gravel. The perimeter of the geomembrane was anchored into the soil. These changes were completed in October 1998, and are described in section 3.4.

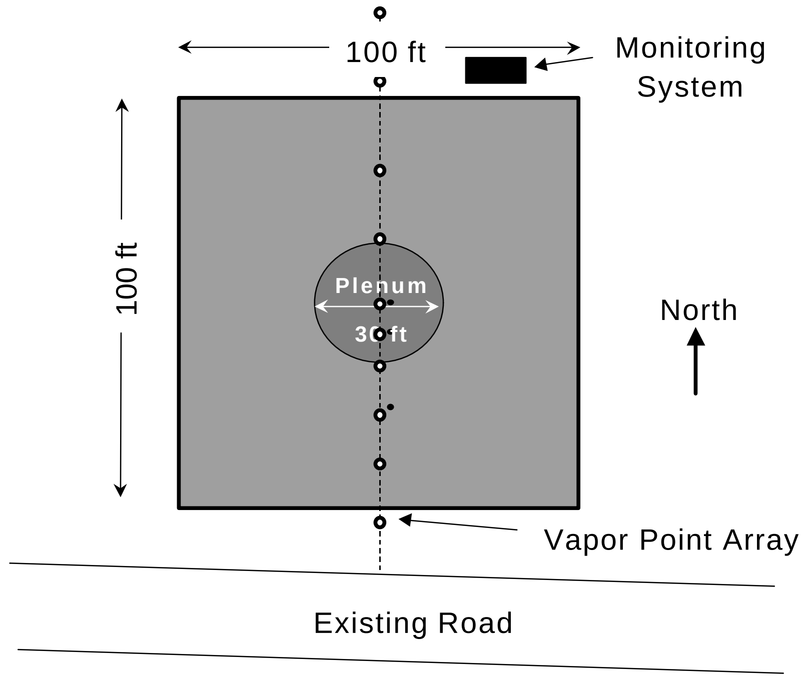


Figure 9. Plan view of BERT™ installation at the RWMC over Pit 2.

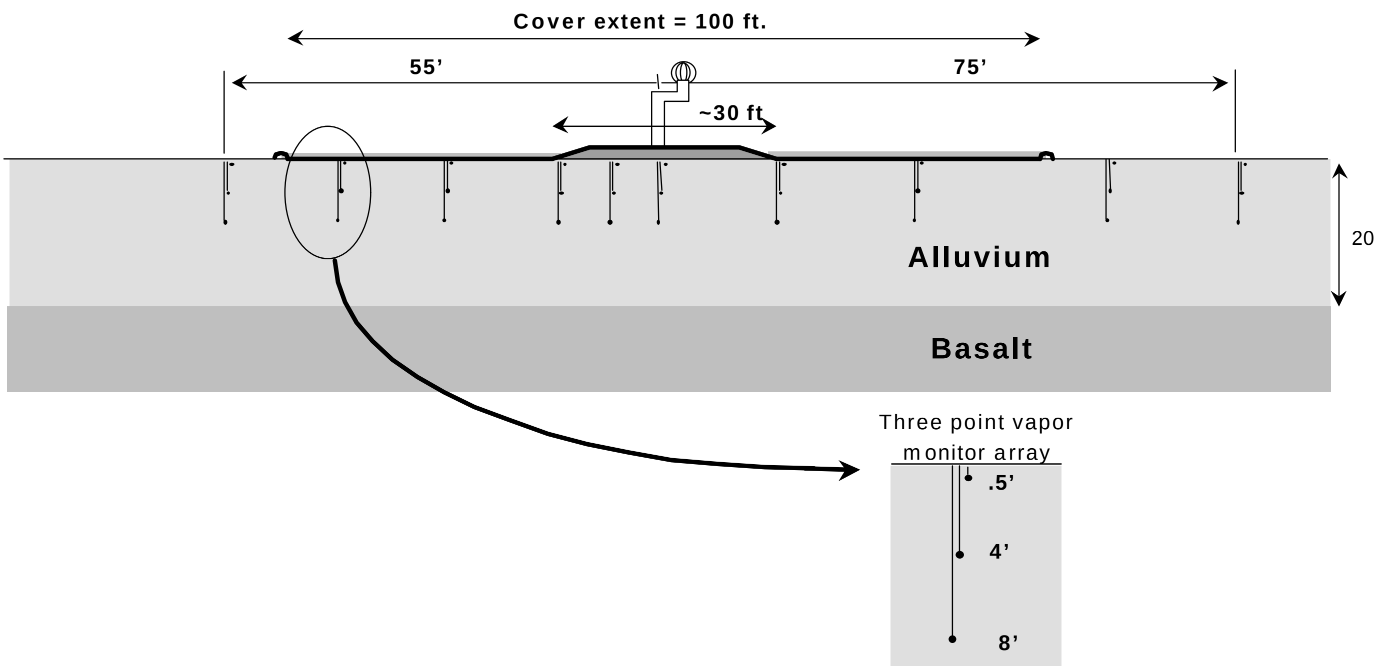


Figure 10. Vapor monitoring point installation design.

Figure 11. Completed BERT™ installation in the spring of 1997.

3.3 Monitoring system

The system performance is monitored by a solar powered, autonomous soil gas sampling and data-acquisition system. Processes of interest were environmental variables (barometric pressure, wind speed, ambient temperature), vent flow, soil gas pressure gradients, soil temperatures, and soil gas composition. The monitoring system, shown in figure 12, measures pressures and samples soil gas through a solenoid manifold array connected to the 30 subsurface sample ports. At 45-minute intervals the system records soil gas pressures, atmospheric and vent pipe air pressures, soil temperature, wind speed, ambient air temperature, and vent system outflow rate. On six-hour intervals, the system also samples soil gas and analyzes for oxygen and carbon dioxide. Manual gas samples are collected periodically and analyzed for the dominant organic contaminants (carbon tetrachloride, trichloroethylene, and chloroform) using a Bruel & Kjaer model 1302 photoacoustic gas analyzer. The measurement descriptions and sensor specifications are listed in table 2.

Table 2. Measurement system components.

Process Measured	Method	Location(s)
Soil gas and barometric pressure	Scanning system sequentially connects tubes running from subsurface sample ports to Setra model 270 barometric pressure transducer	30 in soil, 1 measuring inside of vent pipe, 2 measuring ambient air
Soil temperature	Type T thermocouples	Eight sensors, located at 0.5 and 4' depths
Vent flow	Bidirectional flow measured by low flow orifice plate on vent pipe. Flow is determined using barometric pressure, temperature, and differential pressure across 1" orifice in 4" diameter pipe. Differential pressure measured in two ranges: +/- 0.05 and +/- 0.5 in. water column transducers (Ashcroft model XLdp)	Vent pipe
Wind speed	Rotating vane anemometer (Met One model 5758)	Mounted on vent pipe
Soil gas and vent flow oxygen content	MSA model 485105 electrolytic oxygen sensor (0-25%)	Measures all sample lines
Soil gas and vent flow carbon dioxide content	Vaisala Model GMM12 non-dispersive infrared CO2 analyzer (0-30000 ppm)	Measures all sample lines
All analog signals transmitted to American Advantech conversion modules using 16 bit conversion: model 4017 for voltage signals (pressure, ambient temperature, carbon dioxide), model 4018 for thermocouples, and model 4080D for anemometer inputs.		

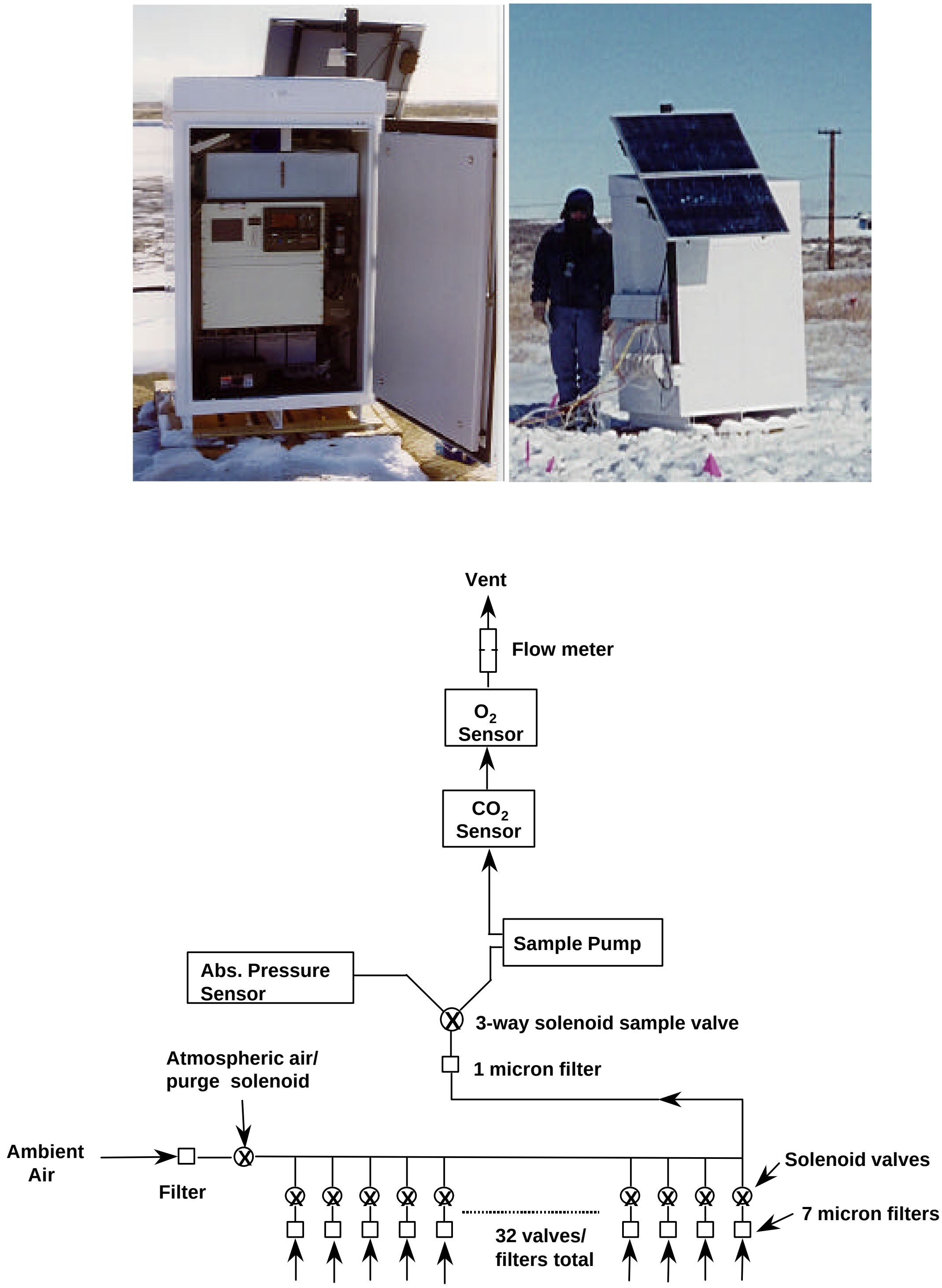


Figure 12. Monitoring system used to evaluate the performance of the INEEL BERT™ field test.

3.4 Design Changes to Capitalize on Wind Effects

In the development of this system it was expected that the barometric effects would dominate its performance. The data shows that wind effects, instead, provide significant boost to the system's performance. Wind boosts the collection plenum vacuum due to the Bernoulli effect, where a high velocity air stream passing across the end of a pipe will induce a vacuum in the pipe. The turbine ventilator is designed to enhance this effect. The area of the collection plenum limits the effects of the vacuum imposed by the wind. If the collection plenum area could be increased, air flow production would increase accordingly.

To investigate the effects an increased plenum area would have on air flow production, a numerical simulation was performed using the T2VOC code. A two-dimensional radial symmetric mesh was generated that represented the original configuration of the collection plenum and surface seal. The soil was modeled as a homogeneous medium, extending downward and outward from the system a sufficient distance to emulate the site scale. The numerical model was calibrated to match actual field conditions, then used as a predictive tool to evaluate different configurations of the collection plenum and surface seal with respect to air flow production. To calibrate the numerical model, the soil permeability was systematically changed until the resultant flow of air matched field measurements. Field test data indicated that, when the plenum was operating at a 15 Pa drawdown (vacuum), the system flowed 15 liters per minute vented air. This same vacuum was applied to the collection plenum area in the model, and the soil permeability which resulted in 15 liters per minute of vented air flow was 15 Darcies.

The numerical model was then used to predict air flow based on changes made to the configurations of the collection plenum and surface seal. The model's mesh was modified to represent a collection plenum 100 ft. in diameter, with no additional surface seal. The outer boundary of the membrane, which contained the plenum, was keyed into the surface soil at varying depths. Results are depicted in figure 13, showing the flow into the plenum as a function of radial distance from the plenum center with the membrane keyed onto a boundary trench 6”, 12”, 18”, and 24” deep. The 6” trench resulted in a flow of 86.8 lpm, and the 24” trench a rate of 71.6 lpm. The difference in flow between the two configurations is the air flowing from the atmosphere around the buried membrane.

The modified design is depicted in schematic form in figure 14. The gravel covering the surface seal was removed, the surface seal rolled back, and a shallow 3” to 6” layer placed on the ground. The surface seal was reinstalled over the gravel and its outer edged keyed into the soil to a depth of 6” to 12”.

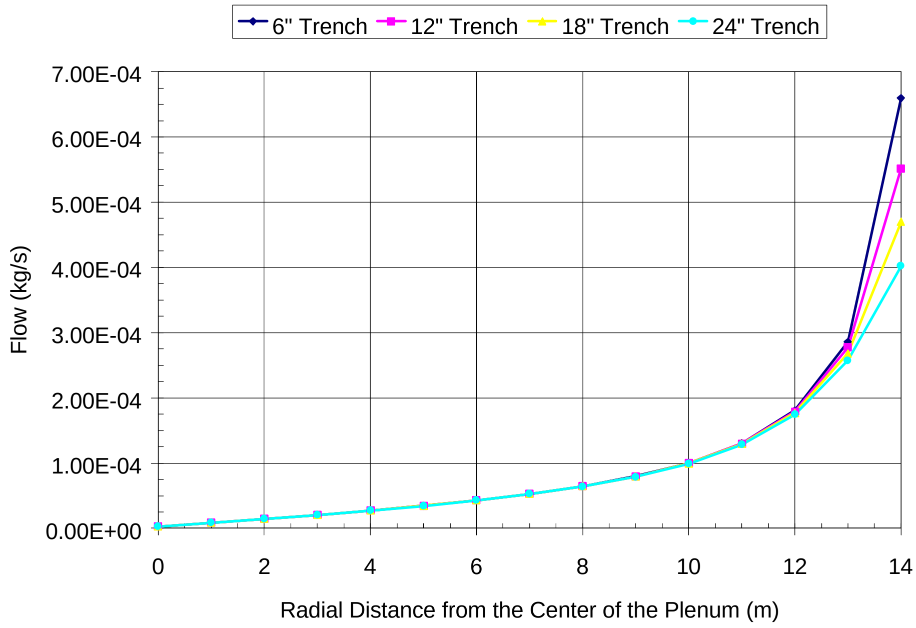


Figure 13. Simulation of modified BERTTM system production under constant plenum vacuum (15 Pa), showing effect of different depth boundary trench.

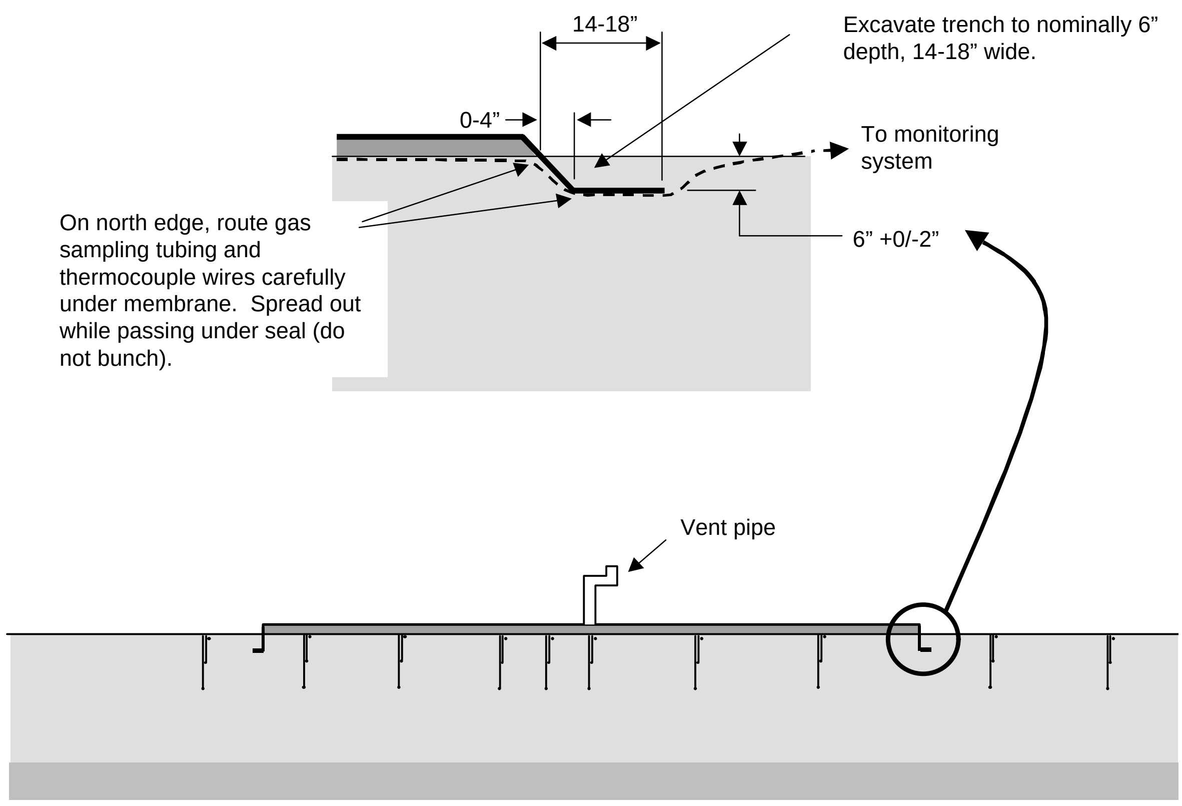


Figure 14. Simulation of modified BERT™ system production under constant plenum vacuum (15 Pa), showing effect of different depth boundary trench

4. SYSTEM PERFORMANCE

Installation of the BERT™ system was completed on December 16, 1996. For the first two months of operation, the weather was particularly cloudy and the monitoring system was receiving insufficient sun to operate continuously. Consequently, test data was intermittent until early February, 1997, at which point the system began collecting data continuously. Key diagnostics of the system operation will be discussed individually in the following sections. Results from both the original barometric configuration and the wind-enhanced configuration will be presented

4.1 Vent Flow

The vent outflow rate is measured with a low flow orifice plate. Incorporating a 1" diameter orifice in the 4" diameter vent pipe, the flow is measured with a low differential pressure sensor. A contiguous period of data is shown in figure 15, indicating the vent flow, barometric pressure, and wind speed (as measured with a rotating vane anemometer). For a short interval of day 79 to day 89 the vent pipe was closed with a gate valve above the orifice plate, illustrating the flow output under zero flow conditions (see figure 13). The window of data represented in the plots is day 1 (Dec. 1, 1996) to day 240 (Aug. 8, 1997). The vent flow and wind speed data have been smoothed with a moving average of 25 data points (smoothed over an 18-hour interval) to more clearly delineate the trends. A magnified window of day 150 to 170 (April 30 to May 20, 1997) is depicted in figure 16.

It is difficult to separate the effects of barometric pressure drops and wind speed on the system vent flow, since high wind speeds are typically accompanied by dropping barometric pressure. The RWMC site also has very few days where wind speeds are essentially zero, which would allow comparison of vent flows due to only barometric pressure changes. There is, however, a clear correlation of high vent flow with high wind speed, such as the period from day 156 to day 157 in figure 16, where high wind speeds existed and changes in barometric pressure were small.

A parametric study correlating windspeed to ventflow, and the time derivative of atmospheric pressure to vent flow, was used to determine whether high wind speeds or drops in atmospheric pressure had the greatest effect on the vent flow output of BERT™. The time period chosen for these direct correlations was April 30 to May 20, 1997. See figure 17 for the parametric plots and their corresponding (r^2). The data represented in this figure has been smoothed (using a 25-point moving average) to average the noise in the data. The wind speed vs. vent flow plot shows a much stronger positive relationship than the time derivative of atmospheric pressure vs. vent flow plot, indicating that wind speed (r^2 = .4443) has a greater effect on the vent flow than drops in atmospheric pressure (r^2 = 0.0284).

Another parametric plot was created to further analyze the influence of winds on the system. It correlates wind speed to vent system vacuum (vent pipe pressure minus atmospheric pressure) over the same (April 30 to May 20, 1997) time period (figure 18). The wind speed plot indicates that when wind speeds are high, the pressure in the vent valve decreases, inducing a relative vacuum in the plenum.

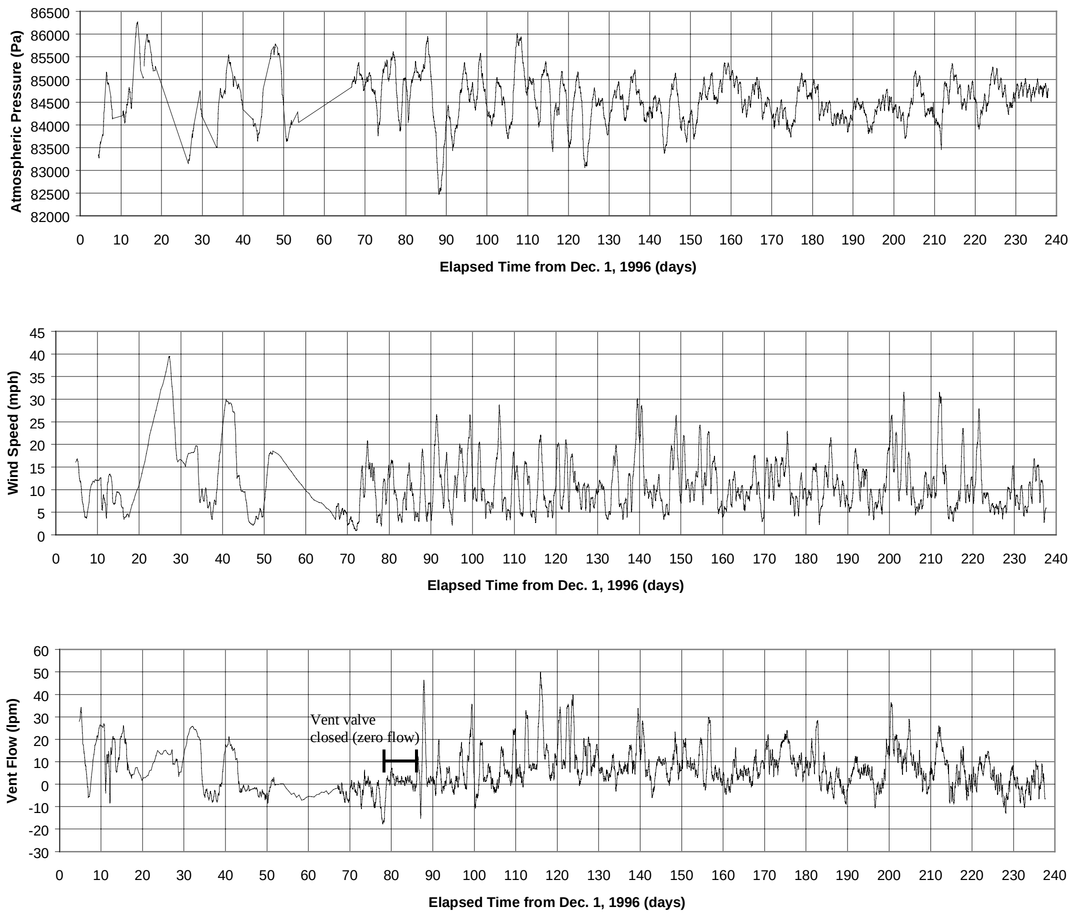


Figure 15. Barometric pressure, wind speed, and flow, December 1, 1996 to August 8, 1997.

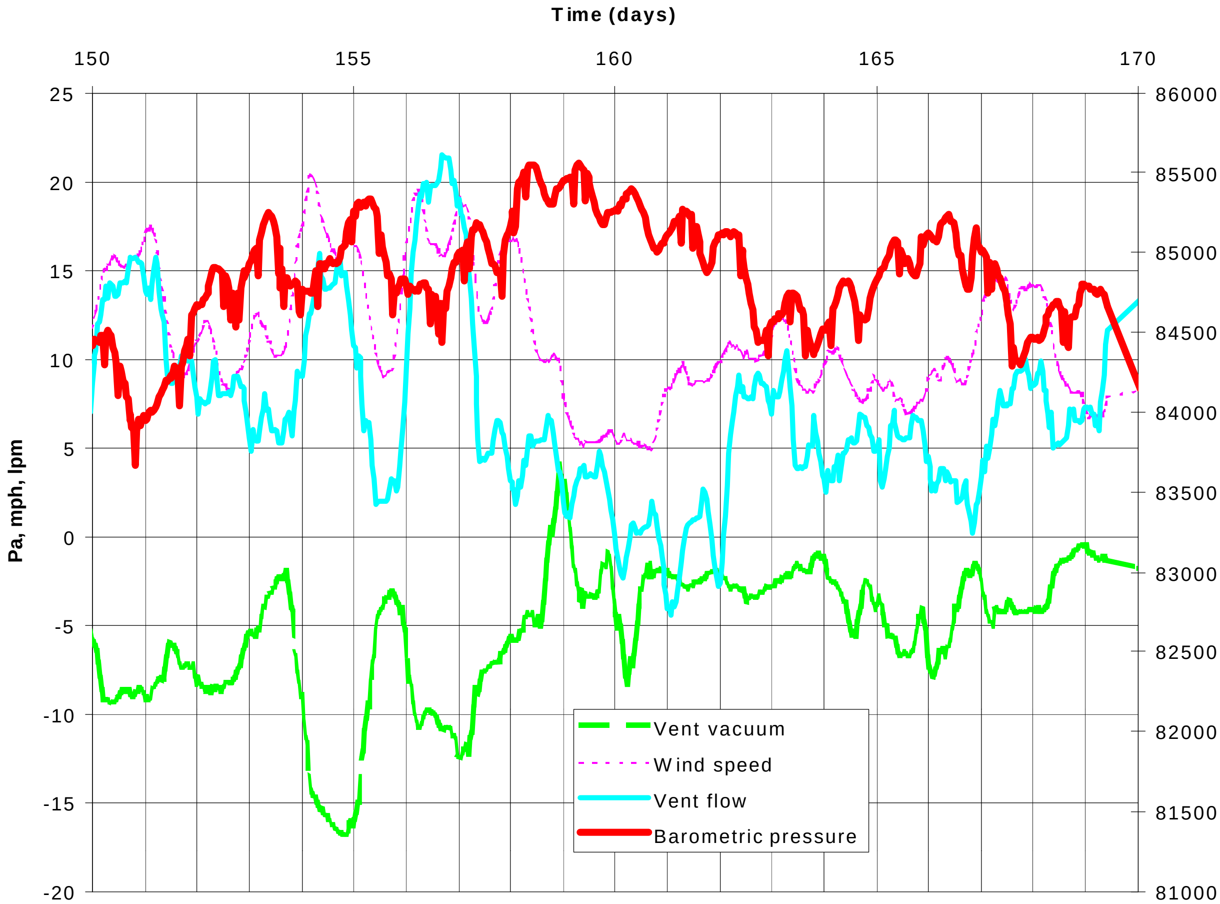
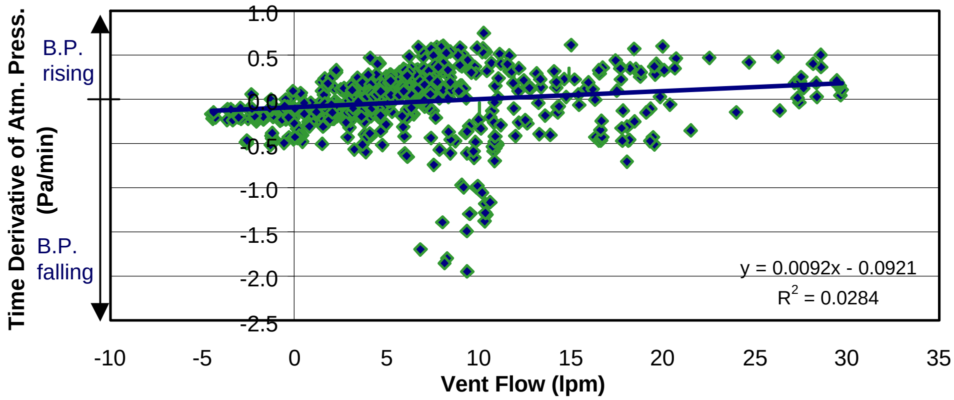


Figure 16. Detailed barometric pressure, wind speed, and vent flow from April 30 through May 20, 1997 (vent flow and wind speed smoothed with 18 hour moving average).



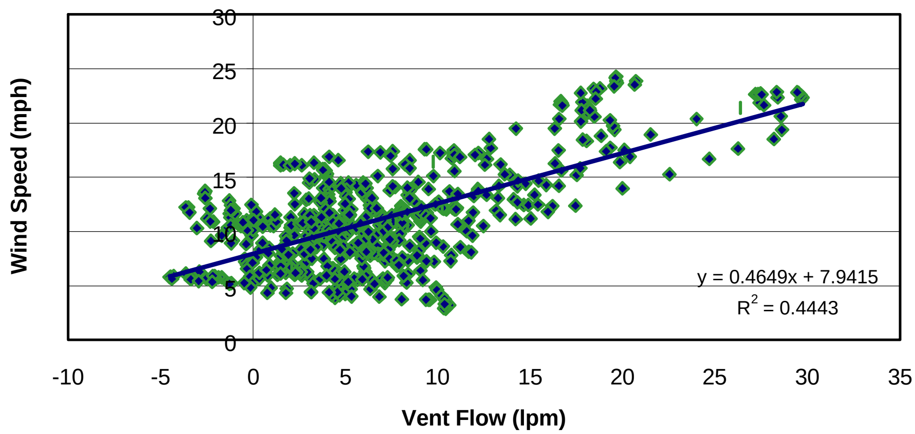


Figure 17. The comparison of these two plots indicates that wind speed has a greater affect on vent flow than swings in barometric pressure.

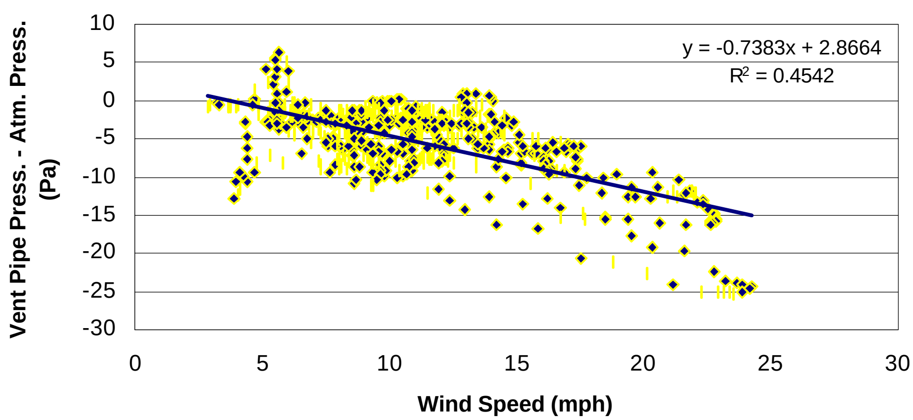


Figure 18. High wind speeds are inducing a relative vacuum in the vent system.

The average vent flow rate over the total operation of the system is 9.0 standard cubic meters of air per day. Sustained peak flows over a one-day interval were as high as 30 m^3/day.

Modifications to the system in October 1998 significantly boosted vent flow production, bringing the average to 34 m^3/day. Figure 19 shows the vent flow, wind speed, and barometric pressure for the initial configuration ("barometric design") and the wind-enhanced design. The gap between the two configurations was the period during which the changes were made. In the latter configuration there is a very clear correspondence between flow and wind speed. Figure 20 shows that correspondence, and also the non-linearity of the relationship between velocity and flow (flow being roughly proportional to the square of the velocity).

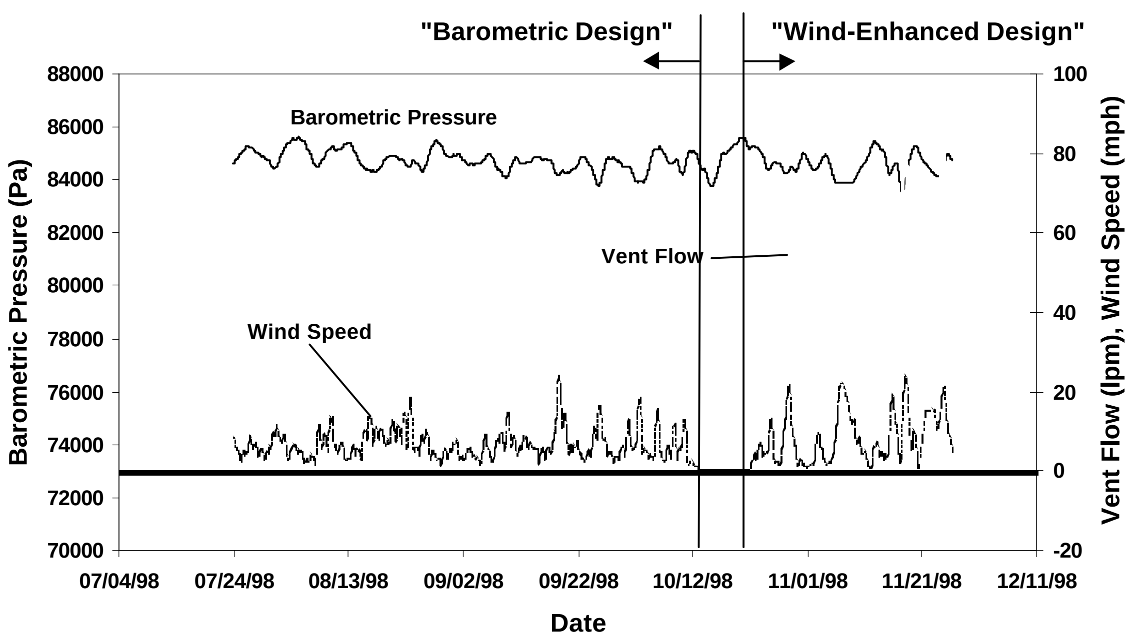


Figure 19. Wind speed, vent flow, and barometric pressure both before and after reconfiguration of the INEEL BERT™ system to enhance wind effects.

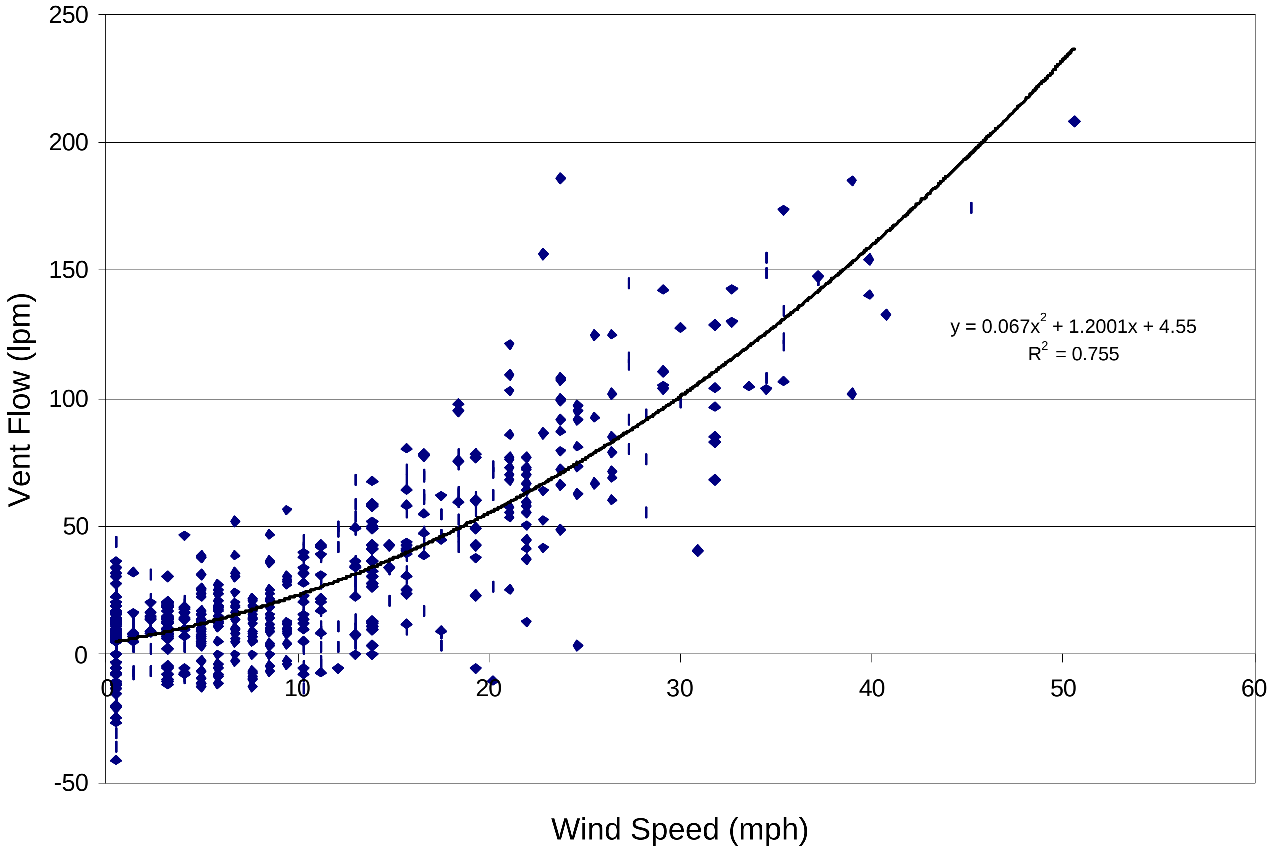


Figure 20. Vent flow as a function of wind speed for the enhanced configuration.

4.2 Soil Gas Pressure

Soil gas pressure is measured with a precision Setra absolute barometric pressure sensor, capable of resolving 0.01 mbar (10 Pascals) change. Data was collected on 45-minute intervals using the same transducer that monitored atmospheric pressure. The sensor was sequentially

valved into the pressure sensing lines to the downhole sampling locations to sample all 30 locations. The system was able to resolve the very small pressure differences experienced in the

In figure 21 a sequence of color contours shows the effect of the surface cover on the pressure field. As barometric pressure is dropping, the pressure field is uniform and very small gradients exist. Soil gas is allowed to rise upward with little restriction because the vent system allows outflow. When the pressure reaches its minimum value and starts to rise, the vent valve closes and induces gradients forcing the air flow around the surface seal into the soil. These are seen clearly in the spectral plots when the barometric pressure trend reverses.

In order to quantify the impact of the surface cover on soil gas pressure gradients, parametric plots of the pressure gradient versus the time derivative of atmospheric pressure at a location under the vent pipe and at a location outside the cover (see figure 22). The pressure

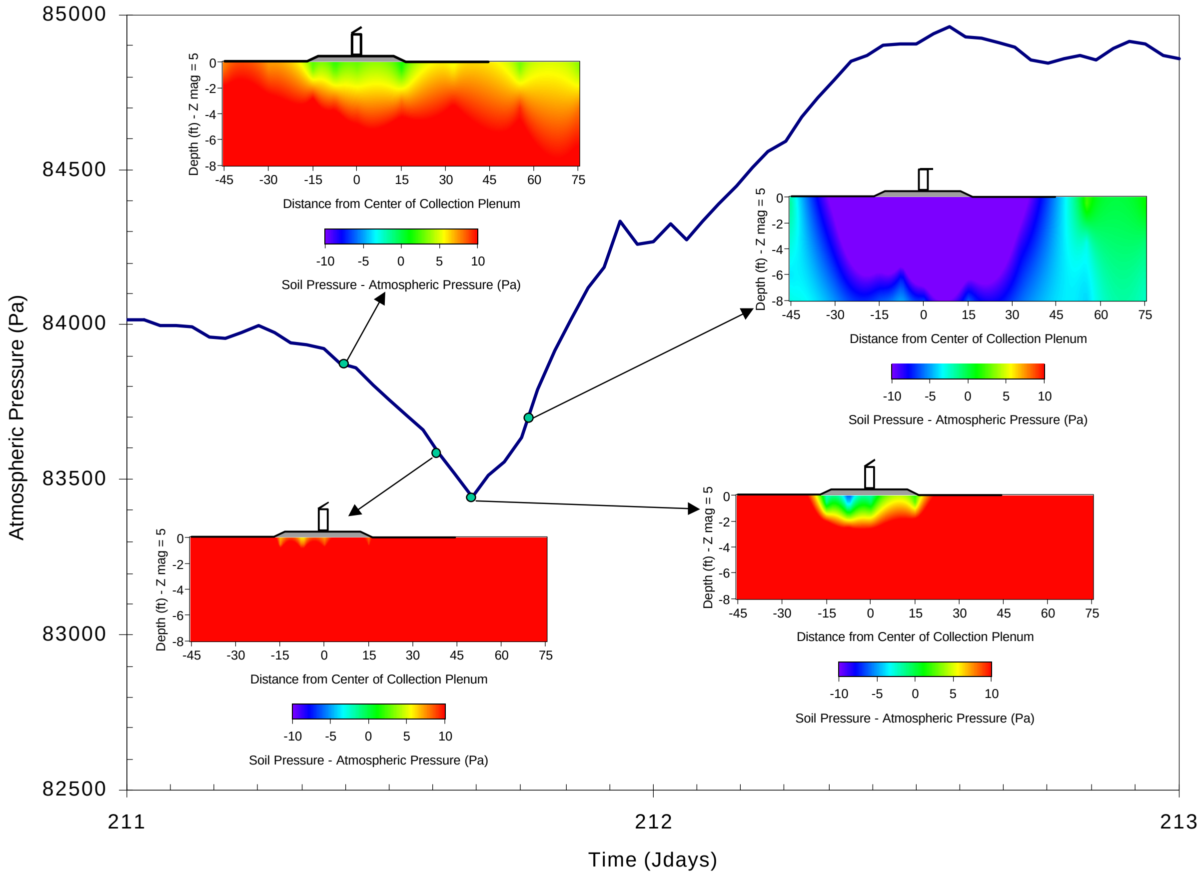


Figure 21. Sequence of in-situ soil gas pressure correlated with barometric pressure. In-situ pressure is expressed as (soil gas press. – barometric press.). Note the distinct change in contours when the barometric pressure starts rising, showing the effect of the surface seal.

gradient is the pressure at the 4-ft depth minus the atmospheric pressure, divided by 4 ft. The time derivative of atmospheric pressure is the change in atmospheric pressure per unit time. At the 75-ft. location, pressure gradients are virtually equal in the positive direction (soil exhaling) and the negative direction (soil inhaling), which indicates that soil gas is moving upward during drops in barometric pressure and downward during rises in barometric pressure. At location 0 ft., which is directly underneath the vent pipe, the pressure gradients are not balanced in the positive and negative directions. The soil pressure underneath the vent pipe is not responding to the rising barometric pressure above, indicating that the surface seal performs its desired function.

After the system modifications the pressures in the vent system showed a very slight vacuum was generated in the collection plenum. The vacuum was so slight that it was in the noise of the pressure measurement (typically less than 15 Pa pressure difference between atmospheric and vent pipe pressure). Although the system was producing much more vent flow in this configuration, the resistance offered by the increased collection area (14 times larger than the original collection plenum) is much lower. This data suggests that the vent system is probably at its maximum flow/minimum back pressure state, and adding vent pipes to the extraction system will increase total flow proportionally.

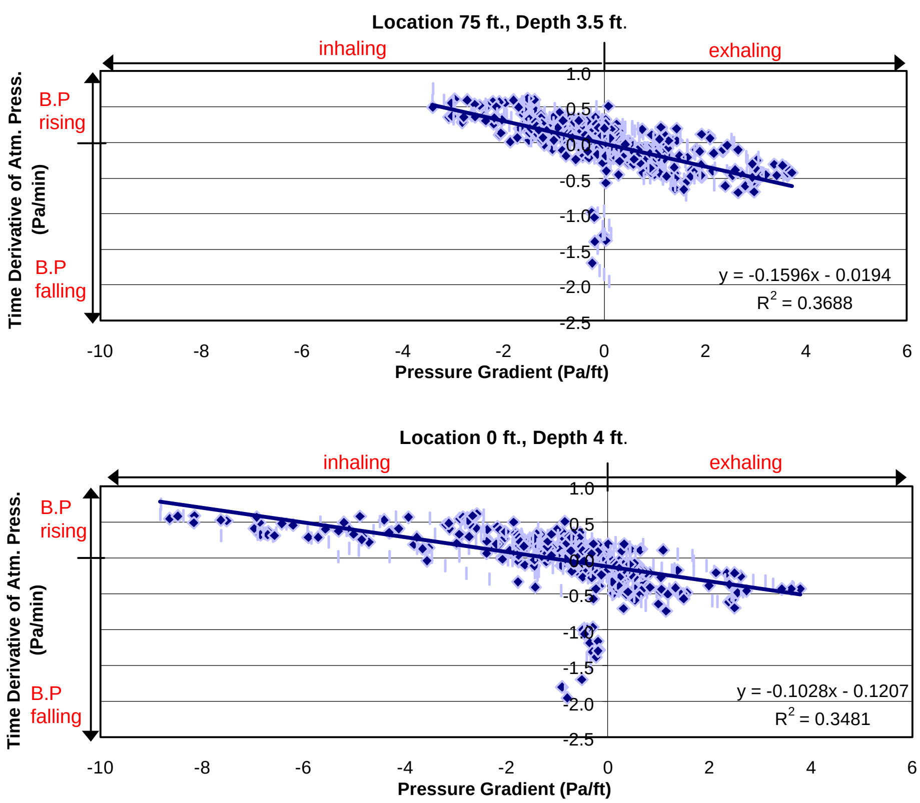


Figure 22. Parametric plots representing the influence or the surface seal on the pressure gradient during rises in barometric pressure. (Data from the April 30 – May 20, 1997 time series).

4.3 Soil Gas Constituents

Soil gas samples are manually collected and analyzed with a photoacoustic gas analyzer on approximately six-month intervals. The Bruel & Kjaer Model 1302 photoacoustic analyzer is calibrated for carbon tetrachloride, trichloroethylene, chloroform, and carbon dioxide.

A detailed soil gas analysis was accomplished prior to system installation, after five months of operation, and after the installation design change in October 1998. The contours for these comparative-sampling runs are shown in figures 23 through 26. The data for each sampling run is listed in tables 3 through 5. High concentrations of contaminants are displaced upward beneath the collection plenum for the data obtained during the original system installation configuration (this was also evident in two other sampling intervals during the original system configuration testing). This is likely due to the surface seal retarding diffusive transport beneath the seal area, causing an accumulation of vapors. After the configuration was changed to capitalize upon wind effects, the concentrations returned to a similar distribution as was seen before the system installation.

Of particular interest to the general fate of buried wastes at this site is the accumulation of very high concentrations of carbon dioxide vapor. Figure 26 indicates the CO_2 distribution in the soil gas both before and after the system installation. Very high concentrations, in the percent range, existed prior to the installation, and even higher concentrations accumulated after the system installation. The plots indicate concentrations as high as 6%. These accumulations were accompanied by significant depletion of oxygen in the soil. The CO_2 accumulations were sufficient to cause some apparent oxygen depletion by displacement, but it is likely that aerobic activity is consuming the oxygen to some extent.

The vented air was also sampled during both the detailed manual analyses and the system's automatic analyses. With the original configuration, concentrations of contaminants in the vented air were typically 90% of the soil gas composition 6" beneath the plenum, indicating that the vented air was slightly diluted with air either from leakage back through the on-way vent valve or short circuiting beneath the surface seal membrane. After the design change was implemented, that number dropped to 50%, suggesting a greater degree of short-circuiting (which was anticipated).

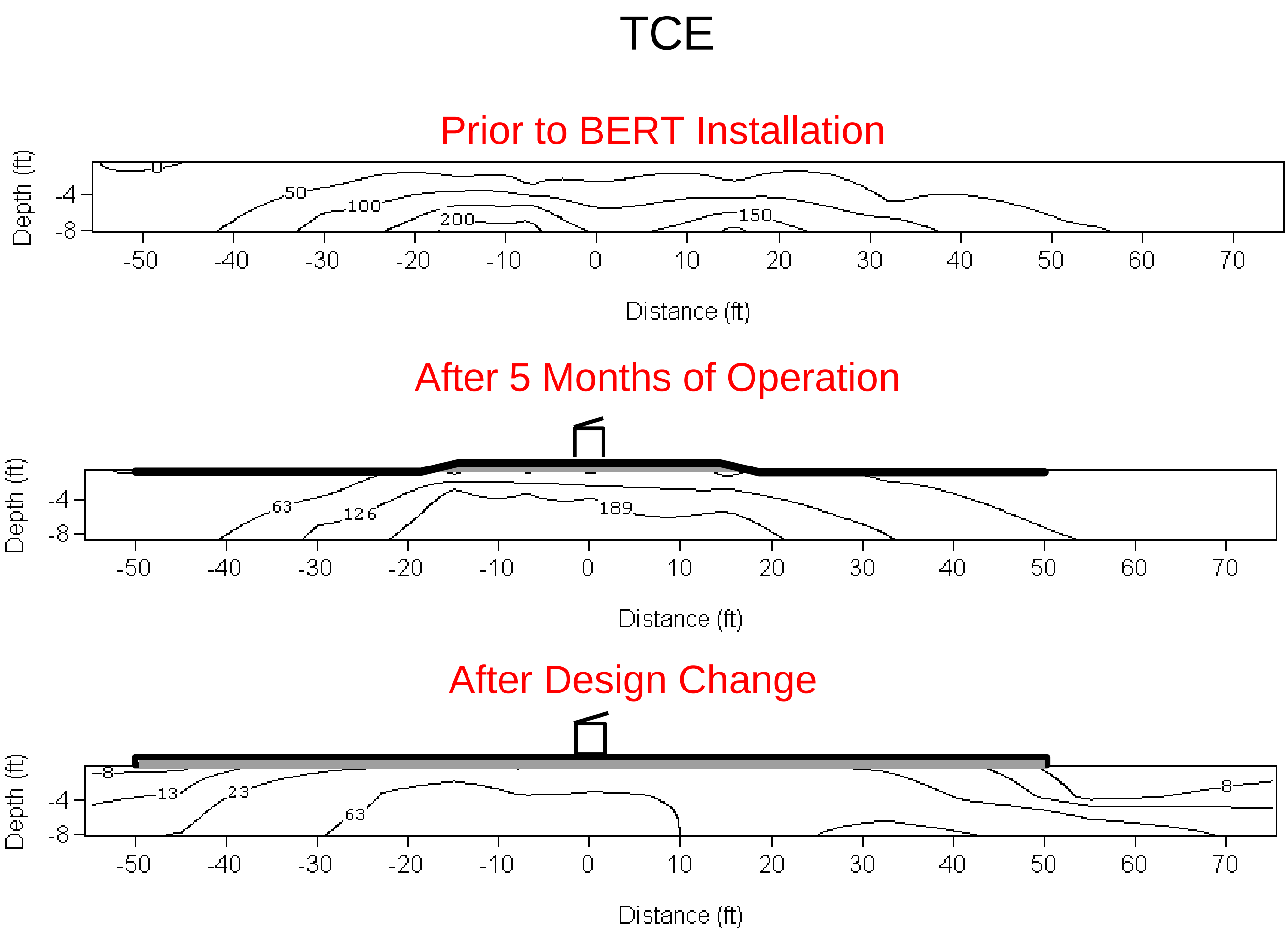


Figure 23. Trichoroethylene vapor concentration prior to BERT™ installation, after five months of operation, and after the installation change.

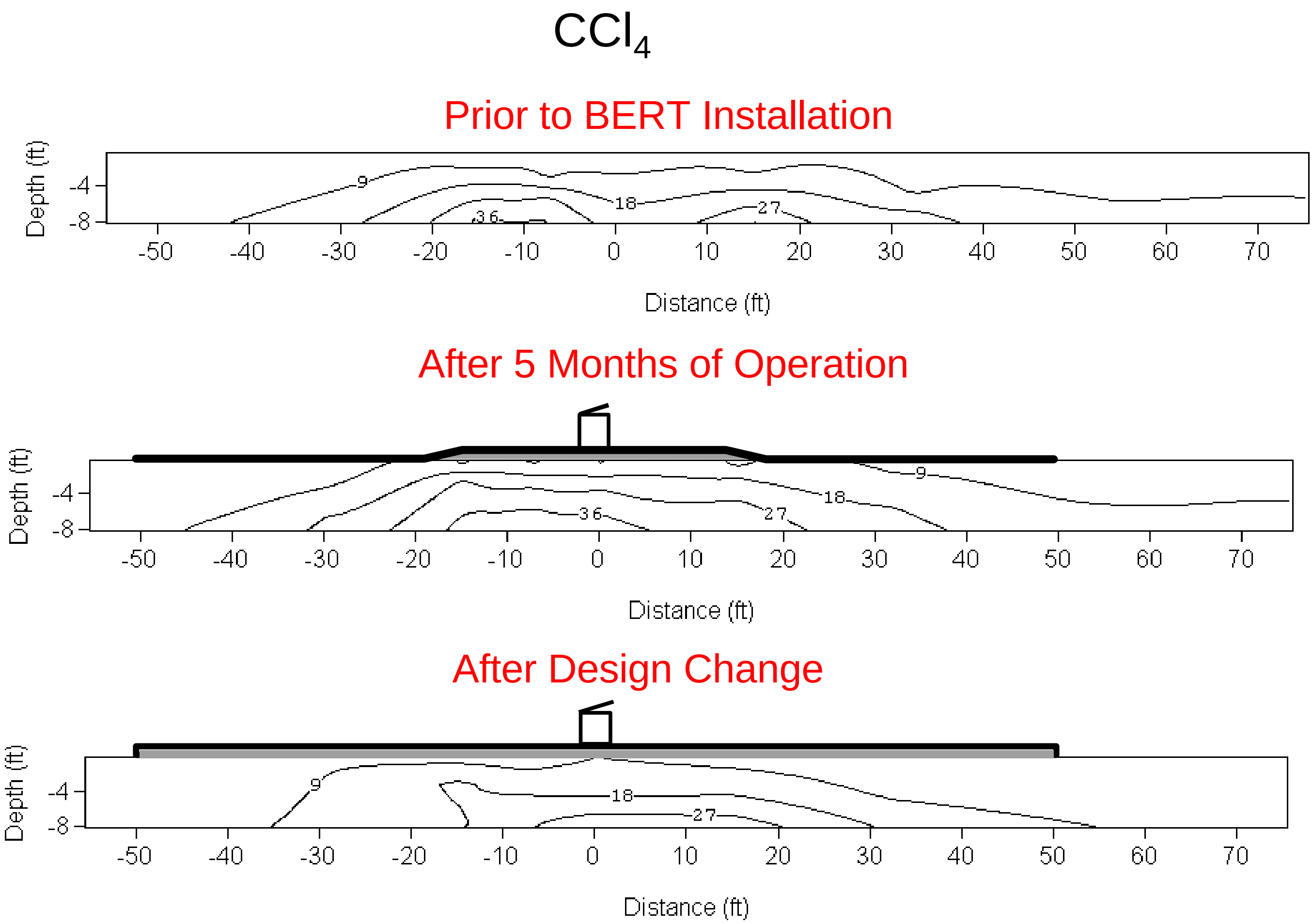


Figure 24. Carbon tetrachloride vapor concentration prior to BERT™ installation, after five months of operation, and after the installation change.

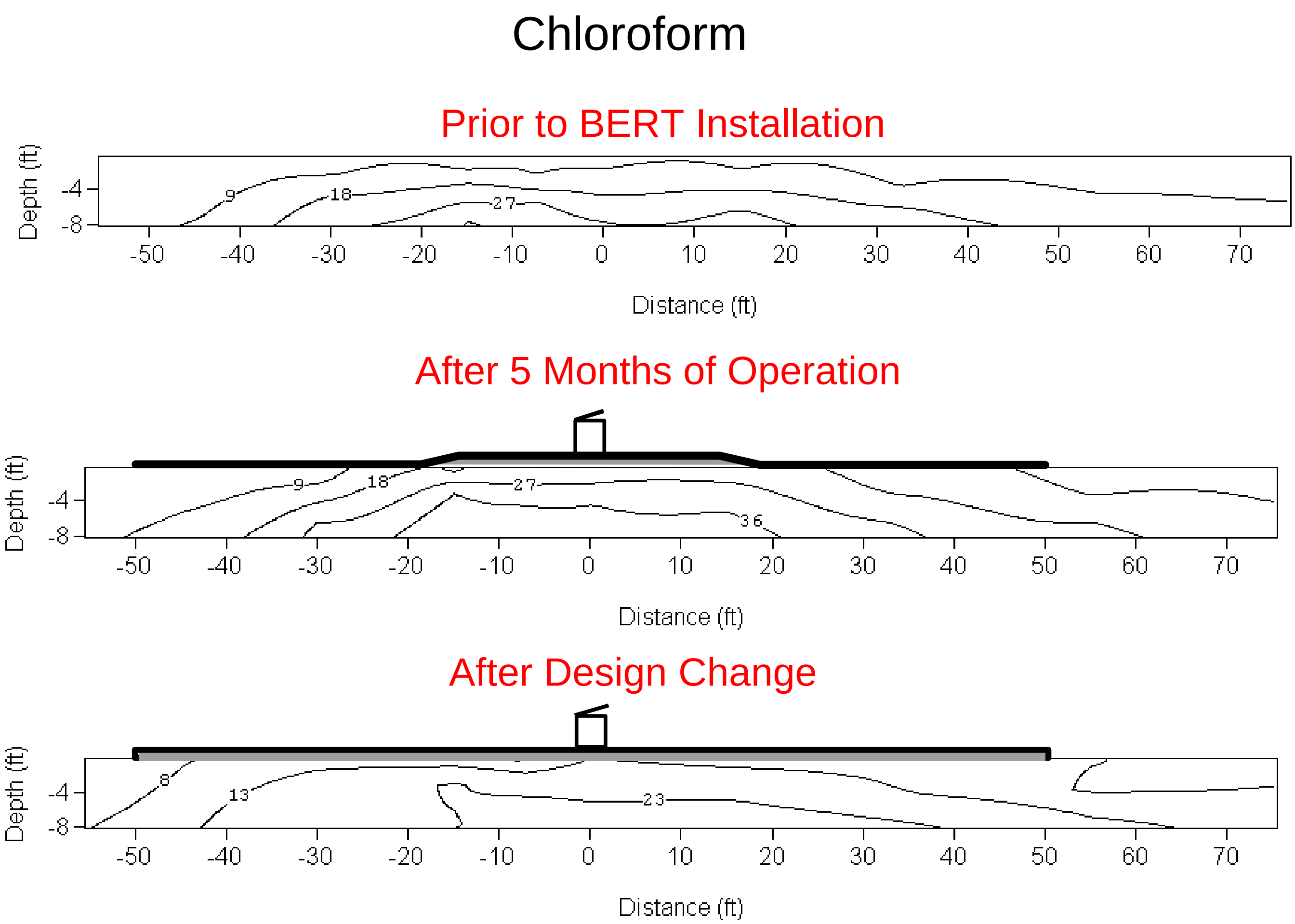


Figure 25. Chloroform vapor concentration prior to BERT™ installation, after five months of operation, and after the installation change.

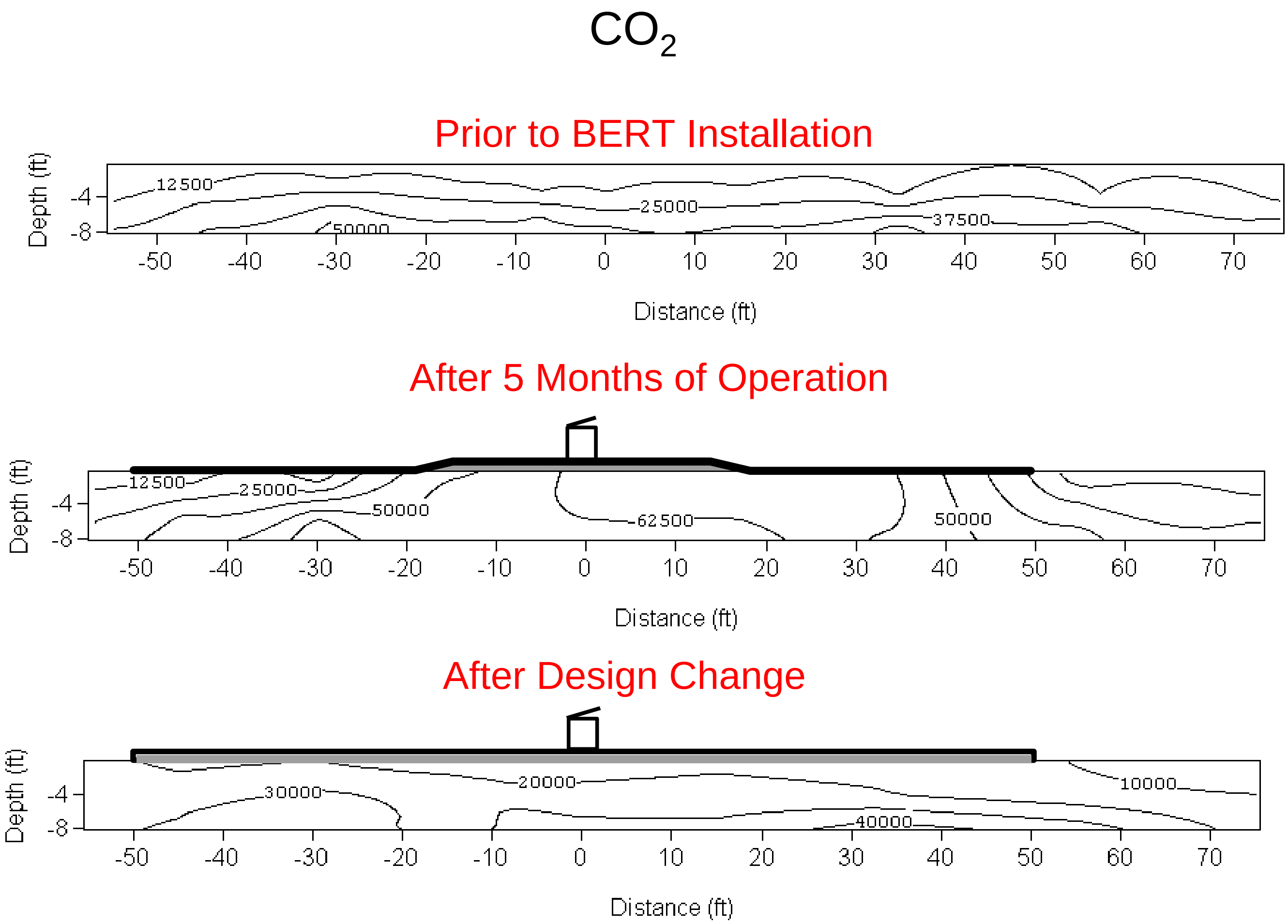


Figure 26. Carbon dioxide concentration prior to BERT™ installation, after five months of operation, and after the installation change.

Table 3. Soil gas analysis taken immediately prior to installation and operation of the BERT™ system at the INEEL RWMC. Location coordinates are referenced as the 0 ft. location at the center of the collection plenum, negative numbers running to the south, and positive numbers to the north.

Date of Testing	Channel No.	Location Coordinate	Depth Coordinate	Chloroform	TCE	CCl4	CO2
(m/d/y)		(ft)	(ft)	(ppm)	(ppm)	(ppm)	(ppm)
12/18/1996	Blank	N/A	N/A	0.228	-0.06	-0.0076	1660
12/18/1996	Ambient Air	N/A	N/A	0.203	0.0585	0.0964	714
12/18/1996	Vent Pipe	N/A	N/A	1.35	0.286	0.316	597
12/18/1996	4	-55	0.5	0.984	0.241	0.203	808
12/18/1996	5	-55	4	3.23	2.31	1.2	10800
12/18/1996	6	-55	8	6.47	10.1	5.55	26700
12/18/1996	8	-45	0.5	3.34	0.877	0.327	1520
12/18/1996	9	-45	6	7.25	24.2	6.02	33400
12/18/1996	10	-30	0.5	2.24	3.57	0.821	1400
12/18/1996	11	-30	6.5	24.6	110	13.7	51400
12/18/1996	12	-15	0.5	1.63	4.92	0.83	710
12/18/1996	13	-15	3	16.7	83.2	14.3	17100
12/18/1996	13 (Duplicate)	-15	3	16.9	86.5	14.9	17200
12/18/1996	14	-15	7.5	36	226	37.1	42900
12/18/1996	15	-7.5	0.5	4.83	19.4	2.78	2780
12/18/1996	16	-7.5	3	11.2	50.7	8.21	9980
12/18/1996	17	-7.5	6	31	192	33.2	37300
12/18/1996	18	0	0.5	5.75	18.2	2.6	3570
12/18/1996	19	0	4	16.1	74.5	13.1	14700
12/18/1996	20	0	8	28.1	144	23.3	43000
12/18/1996	21	15	0.5	4.91	16.4	2.46	3120
12/18/1996	22	15	3	14.1	60.5	10.6	13900
12/18/1996	23	15	8	33.3	217	36.4	42400
12/18/1996	24	32.5	0.5	1.95	16.4	2.13	1240
12/18/1996	25	32.5	4	10	31.8	5.64	12900
12/18/1996	26	32.5	8	26.4	140	24	60900
12/18/1996	27	55	0.5	1.49	11.7	1.46	7560
12/18/1996	28	55	3.5	6.54	16.6	4.22	12200
12/18/1996	29	55	8	18.1	54.3	14.6	47500
12/18/1996	30	75	0.5	0.92	7.31	0.984	987
12/18/1996	31	75	3.5	4.82	8.77	3.43	7110
12/18/1996	32	75	7.5	14.3	28.9	16.7	32100

Table 4. Soil gas analysis taken 5 months after installation at the BERT™ system at the INEEL RWMC. Location coordinates are referenced as the 0 ft. location at the center of the collection plenum, negative numbers running to the south, and positive numbers to the north.

Date of Testing	Channel No.	Location Coordinate	Depth Coordinate	Chloroform	TCE	CCl4	CO2
(m/d/y)		(ft)	(ft)	(ppm)	(ppm)	(ppm)	(ppm)
5/20/1997	Blank	N/A	N/A	-0.847	-0.066	0.281	471
5/20/1997	Ambient Air	N/A	N/A	-0.026	-0.166	0.0665	623
5/20/1997	Vent Pipe	N/A	N/A	19.6	27.8	5.24	65400
5/20/1997	4	-55	0.5	1.53	1.87	0.361	3040
5/20/1997	5	-55	4	5.08	6.6	2.42	21400
5/20/1997	6	-55	8	7.14	10.7	4.64	28000
5/20/1997	8	-45	0.5	1.26	1.56	0.534	3600
5/20/1997	9	-45	6	10.2	30.7	7.21	43000
5/20/1997	10	-30	0.5	2.24	3.57	0.821	1400
5/20/1997	11	-30	6.5	27.7	128	17.9	71000
5/20/1997	12	-15	0.5	15.8	43.4	7.4	47000
5/20/1997	13	-15	3	35.7	225	30.9	57200
5/20/1997	13 (Duplicate)	-15	3	35.4	235	31.6	56700
5/20/1997	14	-15	7.5	44.3	246	37.5	52500
5/20/1997	15	-7.5	0.5	18.7	54.3	7.65	50700
5/20/1997	16	-7.5	3	30.9	194	26	61000
5/20/1997	17	-7.5	6	40.7	262	37.3	54200
5/20/1997	18	0	0.5	20.7	53.7	8.54	69000
5/20/1997	19	0	4	35	214	29.7	68900
5/20/1997	20	0	8	43.3	243	40.2	53300
5/20/1997	21	15	0.5	20.4	40.9	6.24	73300
5/20/1997	22	15	3	32	152	22.5	70700
5/20/1997	23	15	8	40.8	245	35.4	54000
5/20/1997	24	32.5	0.5	11.5	46.2	5.42	66100
5/20/1997	25	32.5	4	20.4	98.9	15.7	69100
5/20/1997	26	32.5	8	31.7	128	21.2	61100
5/20/1997	27	55	0.5	2.34	18.2	1.78	2070
5/20/1997	28	55	3.5	9.41	33.5	6.44	23400
5/20/1997	29	55	8	22.8	60.9	13.4	43800
5/20/1997	30	75	0.5	4.27	12.3	0.892	1660
5/20/1997	31	75	3.5	7.67	18.6	5.68	15000
5/20/1997	32	75	7.5	16.8	32.5	16.3	30800

Table 5. Soil gas analysis taken after the installation modifications of the BERT™ system at the INEEL RWMC. Location coordinates are referenced as the 0 ft. location at the center of the collection plenum, negative numbers running to the south, and positive numbers to the north.

Date of Testing	Channel No.	Location Coordinate	Depth Coordinate	Chloroform	TCE	CCl4	CO2
(m/d/y)		(ft)	(ft)	(ppm)	(ppm)	(ppm)	(ppm)
2/8/1999	Blank	N/A	N/A	1.53	-0.207	-0.06	530
2/8/1999	Ambient Air	N/A	N/A	1.38	-0.153	-0.073	355
2/8/1999	Vent Pipe	N/A	N/A	9.42	18.9	6.78	14500
2/8/1999	4	-55	0.5	3.99	7.09	0.748	22900
2/8/1999	5	-55	4	#N/A	#N/A	#N/A	#N/A
2/8/1999	6	-55	8	#N/A	#N/A	#N/A	#N/A
2/8/1999	8	-45	0.5	7.73	7.35	3.35	17800
2/8/1999	9	-45	6	10	18.3	4.04	29400
2/8/1999	10	-30	0.5	11	19.4	7.94	20400
2/8/1999	11	-30	6.5	21.1	58.5	10.5	39900
2/8/1999	12	-15	0.5	9.04	27.4	6.8	13800
2/8/1999	13	-15	3	24	92	19.4	26500
2/8/1999	14	-15	7.5	22	85.5	16.6	23600
2/8/1999	15	-7.5	0.5	7.61	21.8	5.21	11400
2/8/1999	16	-7.5	3	17.7	57.7	13.7	21300
2/8/1999	17	-7.5	6	30	116	23.7	31600
2/8/1999	18	0	0.5	#N/A	#N/A	#N/A	#N/A
2/8/1999	19	0	4	20.6	72.4	16.2	22900
2/8/1999	20	0	8	30.3	110	33.7	33900
2/8/1999	21	15	0.5	10.7	26.5	6.54	18000
2/8/1999	22	15	3	18.3	59.1	13.3	22500
2/8/1999	23	15	8	32.2	121	23.9	32600
2/8/1999	24	32.5	0.5	#N/A	#N/A	#N/A	#N/A
2/8/1999	25	32.5	4	13.7	32.7	7.2	21200
2/8/1999	26	32.5	8	26.1	86.7	16.3	45200
2/8/1999	27	55	0.5	8.2	3.56	0.503	9710
2/8/1999	28	55	3.5	7.53	6.3	1.19	11700
2/8/1999	29	55	8	14.9	51.8	9.02	35400
2/8/1999	29 (Duplicate)	55	8	14.7	34.9	5.88	29300
2/8/1999	30	75	0.5	6.55	5.64	0.704	4470
2/8/1999	31	75	3.5	#N/A	#N/A	#N/A	#N/A
2/8/1999	32	75	7.5	10.2	17.1	4.94	15200

4.4 Contaminant Removal Rates

The contaminant removal rates are determined by multiplying the vent flow rate the vent pipe contamination concentrations (see table 6). The original configuration vented at an average rate of 9 m^3/day. The modified installation vented at 34 m^3/day. Mass release rates are calculated in table 5. While the vent rate increased after the design change, contaminant mass removal rates did not increase proportionally because the contaminant distribution in the soil was not uniform. As the distance from the center of the collection plenum increased, contaminants generally decreased as shown in the pre-installation contour plots (see figures 23 through 26).

In the original installation, the vent gas concentrations were compared to the soil gas concentrations at the 0.5 ft. depth. If the soil gas concentrations in the collection plenum area are averaged (and weighted as to the area each represents) it is apparent that the vented gas is diluted 10% compared to the near surface soil gas. This could be due to either slight backflow through the vent valve (if it failed to close completely) or short circuiting of fresh air beneath the sealing part of the geomembrane. The same calculation, using the larger collection area of the modified installation, shows that the vent gas is diluted approximately 50% with fresh air. Some dilution was anticipated by flow around the anchor trench.

Table 6. Removal rates of contaminants.

	Baseline Configuration (9 m^3/day)		**Wind-enhanced (34 m^3/day)**	
Constituent	**Concentration (ppm)**	**Rate (g/day)**	**Concentration (ppm)**	**Rate (g/day)**
Trichloroethylene	27.8	1.15	18.9	2.9
Carbon tetrachloride	5.2	0.25	6.8	1.2
Chloroform	19.6	0.73	9.4	1.3
Carbon dioxide	65000	903.2	14500	761.1

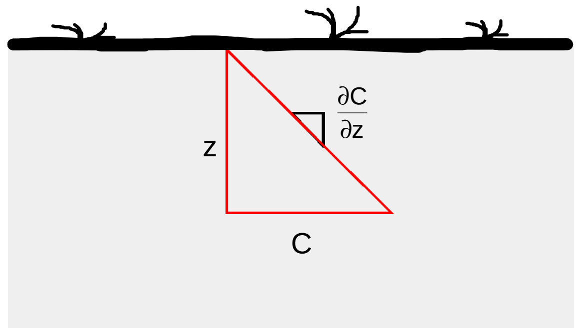
5. ANALYSIS OF NATURAL DIFFUSION OF CONTAMINANTS TO THE ATMOSPHERE IN THE ABSENCE OF A SURFACE SEAL

To be of net positive value, it is important that the BERT™ system installation removes more soil gas contaminants than would otherwise naturally diffuse out of the soil if no surface seal were in place. Flux rates of contaminants to the atmosphere have been measured at the RWMC. They can also be bounded using measured contaminant gradients and estimates of diffusive transport parameters.

Contaminants will diffuse to the atmosphere according to Fick's law of diffusion, where the diffusion rate is proportional to the product of the concentration gradient of the contaminant in the soil and the diffusivity of the vapor in the soil. Diffusivity of vapor in the porous subsurface is estimated by multiplying the diffusivity of the vapor in air by a factor called the tortuosity. Tortuosity accounts for the non-linear path the vapor molecules will have to take through the pore space. Tortuosity can be estimated using the Millington and Quirk model as shown in figure 27, where tortuosity is calculated using the soil porosity and water saturation (Millington 1959). A family of curves is plotted in figure 28 showing the variability of the diffusivity of TCE in a porous media given different tortuosity factors.

Conditions anticipated in the surface soils at the RWMC range from 40 - 50% porosity and 40 - 80% water saturation (personal communication with Jeff Sondrupp, LMITCo). The diffusion constant for TCE in free air is 7e-6 m^2/s. Applying the Millington and Quirk model to this range of conditions yields a range of effective diffusivity from 9.6e-9 to 5e-7 m^2/s. The TCE concentration gradients measured at 10 stations prior to installation of the remediation system are shown in figure 29. To estimate the rate of natural diffusion of TCE to the atmosphere prior to installation at the site, the measured concentration gradient at each station is multiplied by the soil gas diffusivity to calculate surface flux at each station. The range of porosity and saturation was considered to yield a minimum and maximum flux. The results, shown in figure 30, show increased surface flux toward the center of the observation area coincident with the distribution of subsurface contaminant. To estimate the natural, or pre-installation, mass of vapor phase TCE diffusing to the atmosphere over the 100 by 100 ft area, the surface flux at each station is multiplied by a weighted area and summed. Thus, the natural, or pre-installation calculated TCE vapor mass transport ranges from 0.29 to 15 g/day.

Flux measurements were conducted over the Pit 2 area in 1992 and 1993 (Schmidt, 1993). The standard EPA isolation flux chamber method was used to determine contaminant flux at several locations at the RWMC. Locations were chosen based upon evidence of high shallow soil gas concentrations from prior surveys. The TCE measurements at three locations over Pit 2 resulted in two non-detects and one measurement of 0.74 $\mu g/m^2/min$ (1.07e-3 $g/m^2/day$). This value is shown on figure 30 for the purpose of comparing with the calculated value. The measurement lies at the bottom range of the calculated flux, indicating that conditions may not be as conducive to diffusive transport as the upper range would imply. Extrapolating that surface flux to the entire 100 ft. by 100 ft. cover installation yields a total mass transport rate of 0.99 g/day TCE. This is very close to the initial removal rate of TCE from the soil (1.15 g/day) and about a third of the removal rate from the wind-enhanced system (2.9 g/day)



$$\text{Flux} = D_{soil}\frac{\partial C}{\partial z} \qquad \text{(Fick's First Law)}$$

where

$$D_{soil} = D_{air}\frac{(n - nS)^{10/3}}{n^2} \qquad \text{(Millington \& Quirk Model)}$$

D_{air} = diffusivity in free air

n = soil porosity

S = saturation

Figure 27. Diffusive flux model used to predict mass transport of contaminants from soil to atmosphere.

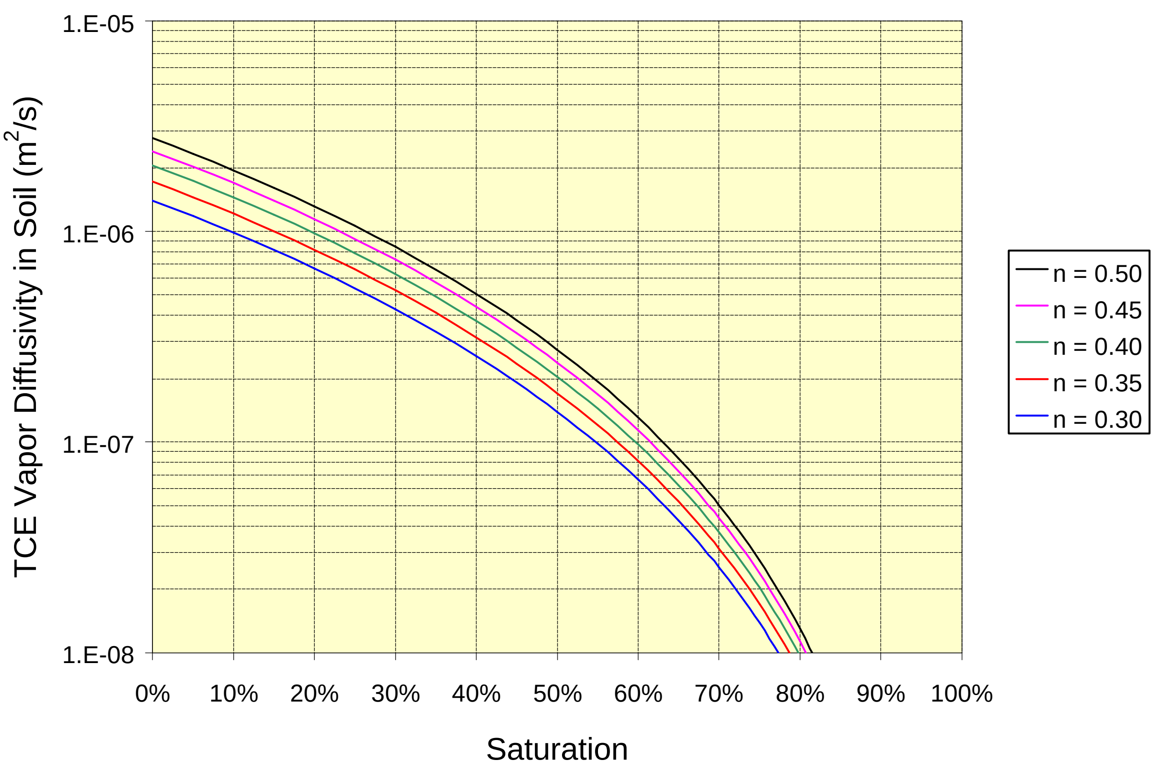


Figure 28. Relationship of tortuosity to soil porosity and water saturation, using Millington and Quirk model (n = porosity).

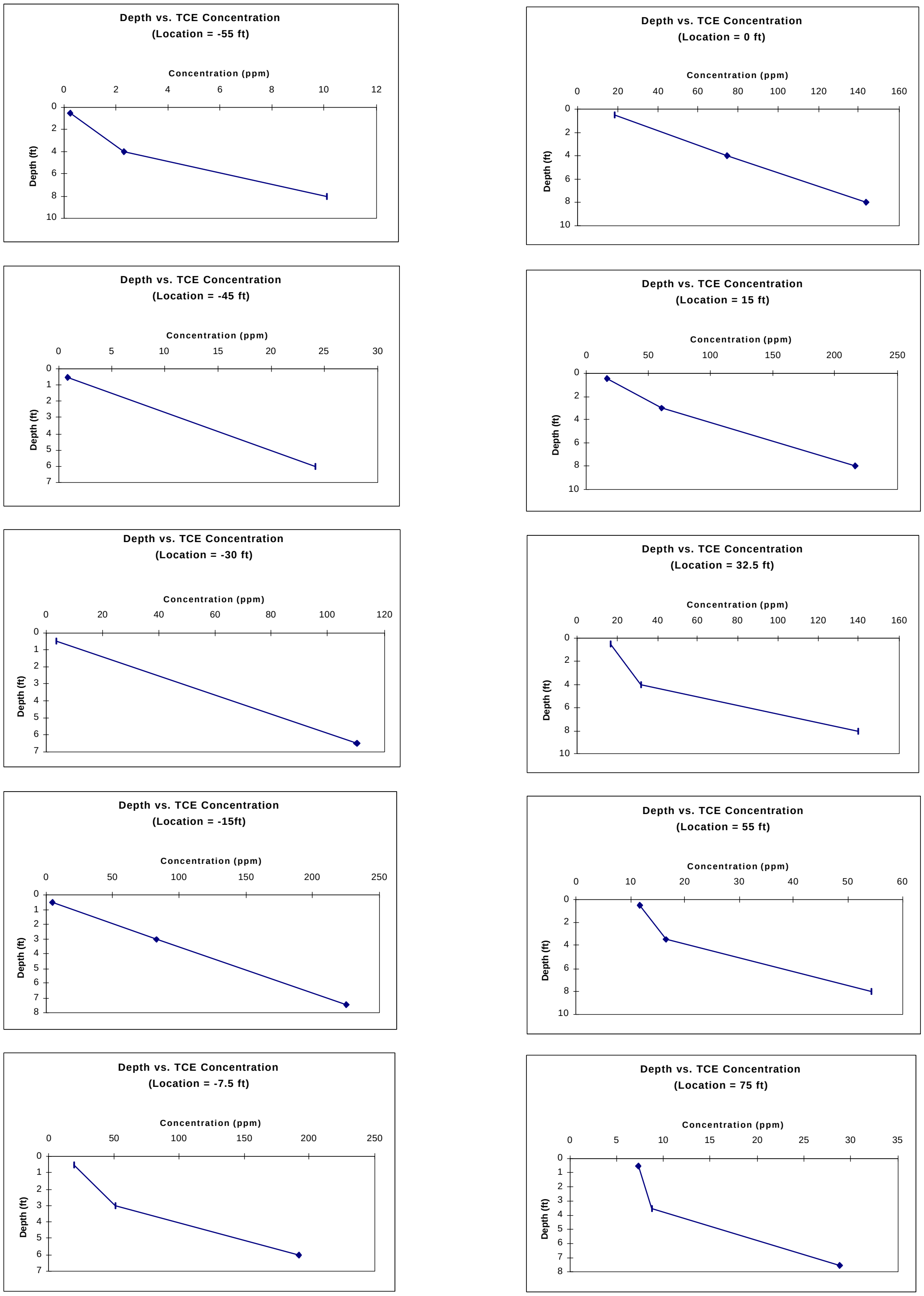


Figure 29. Trichloroethylene (TCE) soil gas concentration gradients prior to BERT™ installation.

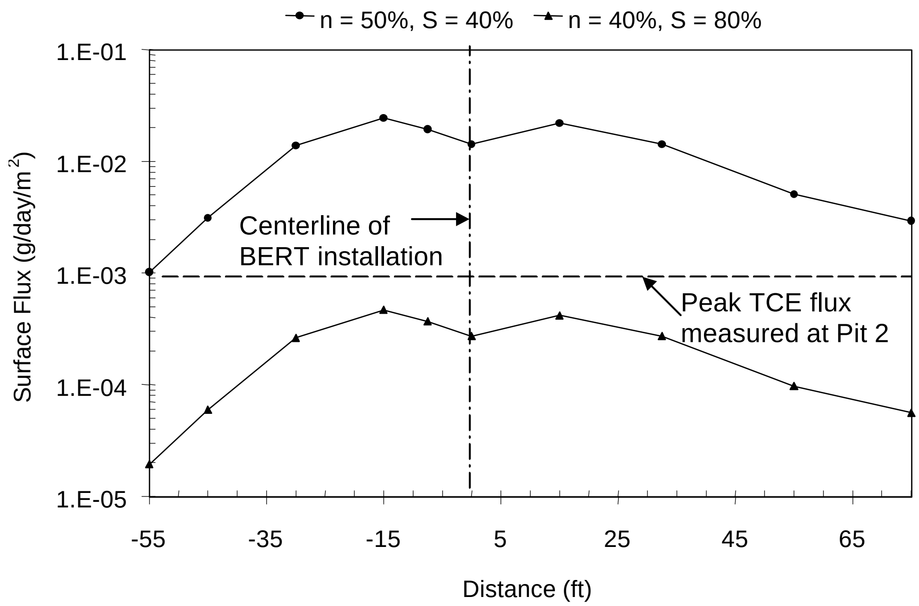


Figure 30. Estimation of the minimum and maximum rates of natural diffusive flux of TCE to the atmosphere prior to the installation of the remediation system. Flux chamber data from Pit 2 measurement is also shown.

6. APPLICABILITY, LIMITATIONS, REGULATORY ISSUES, AND BENEFITS OF THE BERT™ SYSTEM

The BERT™ system is suited to applications in low risk contaminant settings, where rapid response and remediation are not necessary. The original barometric design theoretically required relatively large distances to the most shallow impermeable boundary (like the water table or layers of clay or caliche) to achieve maximum flows. However, the wind-enhanced system does is not constrained by the same limitations. It can be installed at sites with relatively shallow vadose zones and be equally effective as it would with a deeper vadose zones. Suitable applications include volatile contaminants at relatively shallow depths (less than 20 ft.) in the vadose zone:

- Surface spills of fuels and solvents that would otherwise need to be exhumed for treatment, like thermal desorption.
- Leaking buried pipes or pipe galleries
- Underground storage tank leakage.
- Shallow buried waste
- Residual, shallow volatile contaminants remaining after in-situ treatment or excavation and ex-situ treatment
- Asphalt or cement covers over contaminated sites. A BERT™ installation, using the cover as the impermeable surface seal, will vent accumulated contaminants and water vapor from the soil below the cover.

A potentially significant application of the BERT™ design is as an alternate cover design for landfill closures. The system would remove accumulated contaminant vapors from a landfill without increasing moisture content (preventing infiltration). The installed cost would be much lower (at $3.47/ft^2) than RCRA and multilayered geologic covers , which run $4.90 to $14.70/ft^2 (Dwyer, 1998).

The system cannot effectively remediate groundwater, and is not suited to high risk contaminant sites where relatively fast action is required. Since the system operation relies upon modest pressure gradients in the soil, it will not produce significant flows in low permeability soils (such as tight clays).

As with any other passive venting application, the contaminants are typically released directly to the atmosphere with no treatment. At most sites this will be acceptable because the contaminant release rate is well below the regulated emission levels for new sources. If the projected release rate exceeds the screening emission standard, transport and risk calculations may be performed to quantify risk to receptors at defined boundaries.

The BERT™ system removes volatile contaminants at a slow rate while preventing water infiltration into the waste source zone. The benefits of its installation relate primarily to its low cost and risk:

- Installation costs are low because no excavation or drilling is required, and no secondary waste is generated.
- Operating costs are minimal because the system requires no site power and the components are relatively zero-maintenance.

- Risk to workers is very low because no hazardous materials are removed from the site during installation.
- Air emissions are low enough, and dispersed by winds as they exit the vent system, to pose minimal risk to workers.
- Emission rates are sufficiently low to typically be below local or regional thresholds for point source release permitting requirements.

7. SUMMARY AND RECOMMENDATIONS

This project explored the viability of a passive venting and remediation system design that relies solely upon engineered surface features, avoiding the cost and risk of boreholes in contaminated zones. Called BERT™, for Barometrically Enhanced Remediation Technology, the system design capitalizes upon wind effects and periodic changes in barometric pressure to induce net upward flow out of soils contaminated with volatile organic compounds.

The initial emphasis of the system development was to demonstrate that soil gas displacements could be controlled to result in sufficient net upward flow velocity to overcome downward transport from the contaminant source, thereby preventing contamination of the water table. Using analytic and numeric models to assess diffusion, buoyancy, and thermal effects, it was shown in the Phase I effort that sufficient upward soil gas velocities could be imposed by the system to accomplish this, and the system's operating bounds were identified. While wind effects were considered, their quantitative impact was not easily estimated and they were considered essentially a bonus effect. The project proceeded into a demonstration phase in 1996 with the design and fielding of a system installation at a contaminated site.

The initial BERT™ demonstration site was located at the Idaho National Engineering Laboratory Radioactive Waste Management Complex (RWMC). Mixed wastes containing volatile organic compounds (primarily chlorinated hydrocarbons) and radioactive wastes were buried at the site in shallow waste disposal pits, trenches, and soil vault rows. The site geology was considered suitable for the demonstration, with surficial sediment deposits overlaying thick basalt units, and the water table located at 600 ft. The original installation, designed to produce flow based mainly upon barometric processes, consisted of a 100 ft. square surface seal and collection plenum/vent system located at its center. The system was extensively monitored to provide high precision soil gas concentration and pressure distributions over the affected volume. Meteorological and total system vent flow parameters were also recorded.

After over a year of data collection and analysis, two significant observation resulted that suggested needed design changes:

- The system outflow was higher than could be attributed to barometric effects alone, with a strong correlation to wind effects (higher vent flow under conditions of high winds)
- In its original configuration, the system contaminant mass removal rate was on the order of the estimated diffusion rate of contaminants to the atmosphere, had the surface cover not been installed.

These conclusions led to reconsideration of the basic design of the system. Wind effects were analyzed in small scale experiments and the peak vacuum generated on a pipe projecting normal to the wind stream was measured. Several different configurations on the ends of pipes were tested. The greatest vacuum was generated with nothing on the end of the pipe. Wind turbines, which were used during the initial testing period, were found to produce less vacuum at higher wind velocities than were achieved by a plain open pipe end.

The general design of the surface seal was reevaluated. In the initial installation, the collection plenum was about 1/3 of the total surface seal area, located over the peak contamination area. The region of the surface seal outward from the collection plenum served to prevent short-circuiting of fresh atmospheric air into the plenum and also provided a slight boost in vent flow when the barometric pressure transitioned from rising to falling. The net effect of this design feature was not significant, however, and the system flow production could be boosted significantly if the entire surface seal was installed as a collection plenum. Consequently, the installation was modified by placing a pea gravel layer under the entire geomembrane and anchoring the perimeter of the membrane into a shallow trench in the soil. With the increased collection area (and accompanying reduced resistance to flow) the system total flow rate increased to 34 m^3/day, almost four times the previous value. The increased flow was strongly correlated to winds. The vent system pressure data during the windy periods suggested that multiple vent pipes could be installed on the same system to boost the vent flow proportionally.

Comparing with measured and estimated surface flux from the contaminated soil, the modified configuration was now clearly venting more contaminants than were released naturally to the atmosphere prior to the system installation. This is being achieved with the significant added benefit of preventing water infiltration into the contaminant source zone, which is the most likely transport mechanism of contaminants toward the water table.

The BERT™ technology is suited to removal of volatile contaminants at shallow depths in the vadose zone. Applications range from treatment of surface spills and shallow buried waste to a lower cost alternative to RCRA landfill covers. Release rates are typically low enough to not exceed threshold air emission values. It is a slow remediation process, but occurs at almost no maintenance and operating cost. Installation costs are very low (primarily due to the lack of drilling), and because very little soil removal is required risk to workers is minimized.

The INEEL field demonstration indicated the magnitude of flow enhancement that could be realized by designing to capitalize upon wind effects. However, the effect is not completely understood. While it appears to follow a similar trend as seen in airfoil design (being roughly proportional to the square of the wind velocity as in other Bernoulli processes) we have not been able to derive the model explicitly. SEA is performing wind tunnel tests to identify the process drivers and evaluate configurations on the end of vent pipes that would boost vent flow above the present levels. Once the effects are quantified, designing installations and predicting removal rates as a function of wind speed (for a given installation setting) will be much more quantitative. Another data need that would facilitate applications is the vertical wind velocity profile at a given site. Wind velocity is typically very low close to the ground and increases as height above the ground increases. At a given site the profile should be measured so that the height of the vent system can be designed to maximize flow.

8. ACKNOWLEDGMENTS

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